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Agent Based Modeling of Peer-to-Peer Transactions in a Smart Grid Environment

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Resumo

O sistema elétrico está a sofrer uma transformação drástica em direção a um novo modelo operacional, onde os consumidores passivos passaram a desempenhar um papel muito importante. Os consumidores passam a participar ativamente no sistema elétrico com uma variedade de recursos distribuídos de energia, nomeadamente veiculos elétricos, painéis solares, e sistemas de armazenamento de energia, tornando-se nos chamados prosumers uma vez que podem gerar energia. Esta energia gerada pode então ser vendida à rede ou ser vendida a outro consumidor conectado à mesma rede de elétrica. Esta transação de energia, Peer-to-Peer (P2P), pode oferecer vantagens significativas aos consumidores envolvidos bem como ao sistema elétrico em geral.

A utilização de sistemas clássicos de base numérica para modelar as interações dentro de um sistema P2P composto por vários consumidores independentes é um desafio, uma vez que estes têm preferências ou competências diferentes para participar no sistema de energia. A utilização de modelos baseados em agentes, Agent-Baseed Modeling (ABM), pode ajudar a resolver estes problemas. Os modelos ABM incorporam o comportamento individual dos agentes em modelos para entender melhor o comportamento de um sistema complexo e dinâmico de agentes, que tem influência direta nos resultados do sistema. O ABM proporciona uma visão explicativa do comportamento coletivo de um conjunto diversificado de agentes dentro de sistemas complexos. Até recentemente, a aplicação de ABM no sistema elétrico tem sido limitada, mas à medida que o tipo e o número de agentes ativos dentro do sistema elétricos aumentam, os modelos ABM tornam-se mais aplicáveis nestes sistemas.

Nesta dissertação, um modelo ABM é desenvolvido para avaliar os efeitos do aumento da participação dos consumidores nos sistemas de energia locais. Este modelo utiliza um conjunto diverso de consumidores com base em dados reais, para modelar e proporcionar uma visão das interações dentro de um sistema P2P de transações de energia. O modelo ABM é desenvolvido em Anylogic estendido através de Java. O modelo ABM em Anylogic permite a criação de modelos com base em agentes individuais que se comportam de acordo com um conjunto de regras. Isto permite a examinação a nível estratégico ou macro do funcionamento de um sistema de transação de energia P2P. Por conseguinte, são investigados os efeitos das transações P2P nos resultados financeiros, bem como a quota de energia renovável utilizada no sistema de energia local. Os resultados mostram que os modelos ABM podem modelar com precisão os sistemas de trânsito de energia P2P e podem capturar os efeitos do comportamento individual de um grande número de consumidores ativos dentro dos sistemas elétricos.

Palavras-chave: *Agent-Based Modeling, Redes Isoladas, Micro Redes, Trocas de Energia Peer-To-Peer, Prosumer, Energias Renováveis*

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Abstract

The energy system is undergoing a drastic transition towards a system where previously passive consumers will play an important role. These consumers who actively participate in the energy system with a variety of distributed energy resources, such as electric vehicles, solar panels, and battery energy storage systems, become so-called prosumers as they can also generate electricity. This electricity can then be sold to the existing grid or be sold to other consumers connected to the same electric network. This Peer-to-Peer (P2P) energy trading may offer significant advantages to consumers involved as well as the wider electric system.

It is challenging to use classical, numerical based systems to model and understand the interactions within a P2P system made up of many independent consumers who may have different preferences or capabilities to participate in the energy system. The use of Agent-Based Modelling (ABM) can help address these problems. ABM models incorporate the behavior of individual agents into the model to better understand complex and dynamic systems as the behavior of the agents has a direct influence on the outcomes of the systems. ABM provides explainable insight into the collective behavior of a diverse set of agents within complex systems. Until recently, the application of ABM to energy systems has been limited but as the type and number of active agents within energy systems increase ABM models are becoming more applicable to the energy system. In this thesis, an ABM model is developed to examine the effects of increased consumer participation within a local energy system.

This model utilizes a diverse set of consumers based on real-world data to model and provide insight into the interactions within a P2P energy trading system. The ABM model is developed using Anylogic and extended using Java. The ABM model in Anylogic allows for the creation of models using active individual agents who behave according to a set of rules. It provides a strategic or macro-level examination of the operation of a P2P energy trading system. The effects of P2P trading on financial outcomes as well as the share of renewable energy utilized within the local energy system is investigated. Results show that ABM models can accurately model P2P energy trading systems and can capture the effects of individual behavior of a large number of active consumers within electrical systems.

Keywords: *Agent-Based Modeling, Isolated networks, Micro Grids, Peer-To-Peer Energy Trading, Prosumer, Renewable Energies*

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I can do nothing but be humbled by the way my parents raised me with such desperate unconditional love. All I have is theirs and so is this thesis. I hope to make them proud.

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Finally, to everyone who I had crossed paths with during my academic years, thank you for growing up with me. Each and every one of you had something to teach me and I still have a lot more to learn. Good and bad - I would not trade any of it for the world.

Diogo Veiga Guimarães

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"In the morning when thou risest unwillingly, let this thought be present
- I am rising to the work of a human being."
-Marcus Aurelius

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Abbreviations and Symbols

List of Abbreviations

RES	Renewable Energy Sources
ESS	Energy Storage Systems
MG	Micro grids
PV	Photovoltaic
P2P	Peer-To-Peer
EV	Electric Vehicle
EU	European Union
UN	United Nations
GHG	Green House Gases
GDP	Gross Domestic Product
DG	Distributed Generation
ETS	European Trading System
ENS	Energy Not Supplied
MAS	Multi-Agent System

Chapter 1

Introduction

This chapter presents the introduction to the topic while also tackling the motivation for this thesis, the research objectives, the methodology used and the thesis structure.

1.1 - Background

The electric power system has since long been structured vertically - starting at the production level, going through the transmission, distribution and finally consumption of electric energy. This is also referred to as a hierarchical structure [1]. This implies that the energy flow is unidirectional, only having production at one level (highest level) and consumption at the other (lowest level) [2]. The simplicity of this architecture is its main strong point. However, taking into account the long distance between the levels (which cause big expenses on infrastructure and big transmission losses [1]) and the implied fact that if there is a problem at a higher level, all subsequent network elements are affected, it's easy to see there are relevant issues to be taken into account [3]. Furthermore, generally speaking, power plants are associated with issues such as pollution - specifically, significant greenhouse gas emission [2], [4], [5] (which justifies building them farther from places of consumption (e.g. heavily populated centers) - the need for specific conditions (e.g. hydro power, wind power) and/or negative impact on flora and fauna and local settlements [3], [6]–[10].

This has led to a lot of attention concerning energy production and clean energy alternatives, looking at an environmentally conscious future for the power industry [11]–[14]. Laws and treaties have been put in place in order to achieve a greener future, which comes at the expense of significant changes in the current paradigm, with a lot of focus in the power system [15]–[19]. In this context, there has been a growing interest in renewable energy sources and technology [4], [5], [10], [13], [20], [21].

However, these technologies come with their own constraints:

- high volatility (unpredictable and inconstant resources);
- high economic burdens (researching, building, installing, operating and maintenance costs);
- the need to adapt the transmission and distribution network infrastructure;
- negative impact on ecosystems;
- low overall efficiency;
- being limited geographically by land and resource availability;
- lack of rotating inertia associated with synchronous motors used in conventional power plants (ineffective response to variations of load and frequency, translating to technical unreliability).

In tandem with grid voltage rise, reverse power flow and power quality problems derived from the would-be high Renewable Energy-based Distributed Generation penetration in the power system [2], [10], [14], [21], [22] these technologies become less attractive, despite the necessity of a change.

Given the continuous growth of the world population and rising economic development, coupled with the adoption of new technologies, a growing energy demand can be expected [10], [14], [16]. In light of all this, the electric power system as it was designed had been facing a crescent amount of challenges. Thus, new possibilities began to be explored, namely the desegregation of the hierarchical system and an evolution towards a liberalized market, the implementation of automated systems, intelligent technologies and modular generation technologies for decentralized use (e.g. photovoltaic panels and wind generators in distributed generation) [5], [11], [16], [22]–[24].

This meant, however, that there had to be investments and incentives from world governments to promote and adopt distributed generation while the technologies matured. The adoption of distributed generation would bring advantages such as the reduction of losses by transmission [14], [22] (by having production closer or local to the loads) and the reduction of investment in the network (enabling developing countries and rural places to produce energy without depending solely on the grid) [11], but overcoming technical, economic, managerial, political and market barriers worldwide cannot be expected to be an easy nor immediate feat [10], [25]. The end result, however, would be a greener, more reliable and efficient electric energy system.

As a consequence of this new direction towards a more liberalized market seeking the integration of distributed renewable generation, a new type of proactive consumers appeared, called "prosumers". Prosumers would have the capabilities to both produce and consume energy - bringing with them a range of new opportunities and challenges to the operation of the power system and the energy markets [20]. Energy would now have to flow bidirectionally (from the grid to the consumer but also from the consumer back to the grid) as production surplus could be sold and fed back into the grid for a small financial return [4], [23].

In recent years, an even bolder concept was created: "peer-to-peer" (P2P) electricity markets. According to it, the surplus in production of electricity could be bought and sold between prosumers and other consumers at an agreed - usually lower - price than the price at which they would buy electricity from the grid [15], [20], [23]. This concept presents a radical change that would increase the resilience and stability of the network (by decreasing the overall demand from the grid's point of view and not injecting the surplus energy in the grid, which would lead to technical problems). Other benefits include the promotion of energetic self-sustainability and of the free market, as individuals would be able to produce, consume and sell energy themselves. In this case, the grid would act more as a backup safety net and dependency on it would decrease [11], [15], [23]. Furthermore, as small scale energy production is generally dependent on renewable resources [20], this change would represent a positive step towards a sustainable future. With this in mind, the concept of "energy communities" was recognized by several political entities and several projects featuring this concept began to be explored [17]–[19], [21]. Energy communities are aggregates of entities who generate and consume energy within themselves, before relying on the electric grid. A step-up from a sole prosumer, a community can include both prosumers and consumers as can be seen in Figure 1.1. The common goal is to minimize dependency on the grid by using mechanisms such as load-shifting and energy storage systems to flatten the demand curve and be self-sustainable as a community - even if it is impossible to be self-sustainable as an individual [26]. Most communities rely on RES-based generation, encouraging the possibility of a self-sustainable, reliable, net zero community concept being popularized, which aligns with most countries' environmental policies and global needs [27].

By applying Multi-Agent Systems (MASs) to energy optimization problems, it is possible to simulate an environment where different entities with different behaviors interact. This enables system modeling that is "robust, scalable and context-aware" [28]. An environment can be designed to play a role in influencing entities with different generation/consumption profiles, which allows to emulate real-world interactions and draw useful conclusions that take social factors into account. This is important, of course, when discussing a highly variable and social environment such as a community cooperating in peer-to-peer energy trading. It allows to simulate the behavior of entities with different "needs", "wants" and "cans", exposed to more or less specific environmental conditions. A community has to set rules in order to ensure equal rights and benefits, particularly in the likely event that only some entities in a community are capable of generation, only some own storage units, and all have different consumption patterns [29]. Furthermore, an entity might place more value in minimizing costs, and another might place more value in comfort (which are frequently mutually exclusive) - and these might have varying degrees of importance in time for each entity. It is not only a technical problem, with technical limitations to be resolved by simply using better suited materials or larger equipment. MASs comes as an indispensable aid in previewing and managing what is to be expected from a social interaction inside a community - paramount if this concept is to be proven and popularized.

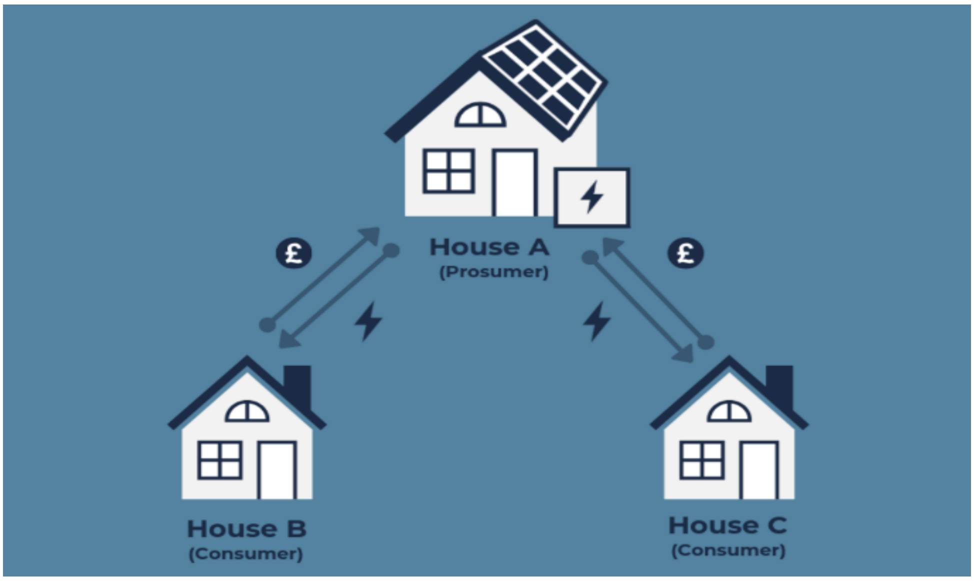

Figure 1.1 - P2P energy trading.

This study sets out to prove the feasibility of the operation of P2P energy markets both financially and technically, proving that they have a place as an interesting alternative to the conventional paradigm.

1.2 - Problem Definition

It stands to reason that, in the current poor economic state of the world, following a global pandemic, resources will be directed towards healing the economy rather than on growth for a while, discouraging the possibility of inviting subsidies and other incentives for some time, which does not help address the social and financial concerns. In a future without relevant subsidies to make self-consumption an appealing option, a strong model will have to be in place to make energy communities a reality. To achieve that, the model would have to be scalable (e.g., PV modules) and address the volatility and uncertainty of renewable energy alternatives (e.g., with energy storage and energy sharing). Instead of selling excess production at market price back to the grid – which is unprofitable and strains the grid - prosumers would have the opportunity to share the energy locally (Peer to Peer trading).

A model utilizing renewable resources and an energy sharing concept should take into account the personal preferences of the user, considering both a cost-minded approach and a comfort-driven approach, which are conflicting variables since more comfortable preferences can be assumed to imply higher costs. Also, the seasonality of the resources and the environment (average temperature, average daylight time and average daylight intensity, for PV) can be expected to impact the results. It should also accommodate the idea of a varying number of people per residence (which impacts the hourly consumption graph). Conventional approaches (mathematical optimization and forecasting) are usually not optimal choices for taking behavioral and communal dimensions into account.

Recently, Multi-Agent Systems (MAS) modeling has been getting a lot of attention in order to tackle this nuance, being presented as a good alternative to represent decentralized socio-technical systems. Therefore, it is necessary to develop a MAS model to examine the effects of increased consumer participation within a local energy system, and at the same time, have in consideration a diverse set of consumers based on real-world data to provide insight into the interactions within a P2P energy trading system.

1.3 - Research objectives

The main objectives of this dissertation are:

- To carry out a comprehensive literature review on the area of energy markets and energy trading;
- To develop an agent based Peer-to-Peer model on smart grid environment to examine the effects of increased prosumer participation within a local energy system;
- To carry out several case studies that simulate different operational scenarios;
- Analyze the effect of the various agents in the transactions and perform a sensitivity analysis on key variables in the model performance.

1.4 - Research methodology

The work developed in this dissertation sets out to prove the feasibility of the operation of P2P energy markets both financially and technically, proving that they have a place as an interesting alternative to the conventional paradigm. In order to achieve the proposed objectives for this work, a based agent model is developed, that accounts for P2P transactions. The proposed model was coded in Anylogic 8.7.4 and Java script. All simulations are conducted in an Asus laptop with an Intel i5 processor, clocking at 2.30GHz frequency.

1.5 - Thesis structure

This dissertation is divided into five chapters. In chapter 2, the state of art and the concepts related to the topic being studied are presented. Also, the global goals and legislation surrounding these themes are mentioned, and the Portuguese context is explored in particular. Furthermore, there is a bibliographic review of relevant works on the subject of the dissertation. Chapter 3 addresses the tools and conditions used for the model, including the software, the model conditions and assumptions made. Some code examples are included to highlight the strengths of the software. In chapter 4 the case study, the simulation results and their analysis are presented, focusing on the energy mix under different conditions. A financial analysis of the results is also included. Finally, in chapter 5, the relevant conclusions are presented, as well as possible future work. Works that resulted from this dissertation are highlighted.

Chapter 2

State of the Art

This chapter presents the state of the art and the concepts related to energy communities and P2P business models in the presence of Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs). Relevant literature regarding the current legal paradigm and active business model examples of P2P energy trading is also presented. Finally, an overview of the bibliographic review is also presented, highlighting the relevance of the present work in comparison to those most similar to it.

2.1 – Renewable Energy Sources

In the following subsection, context is added regarding the role of RES in the Energy Transition, while discussing global goals and legislation and the Portuguese context in particular. Also, the technical challenges related to the integration of this technology in discussed.

2.1.1 Following the Energy Transition

Booming technological and economic development has led to an increase in energy demand worldwide. In 2020 the world population is 7,794,798,739 - in 20 years it is expected to have increased by 25% [30][33]. The need to adapt quickly is alarming. The obvious answer would be to simply match this rise with an increase in production. However, there are pressing issues that have forced a shift in the traditional point of view [31]:

- Environmental concerns, mainly related to greenhouse gas emission and an increasing carbon footprint.
- High transmission losses, as conventional production is generally distant from consumption points.
- Increased congestion from a rising demand.

To tackle these matters, countries all over the world gradually started taking action, as shown in subsection 2.1.2 "Global Goals and Legislation". In recent years, the power sector has been under transformation, reforming or shutting down large fossil fuel-based power plants in favor of RES-based distributed generation. Local generation units, close to the consumption sites, are a major advantage in dealing with the aforementioned problems. Known as distributed generation (DG), this type of generation is mostly comprised of RES-based technologies like solar farms (but also wind, mini-hydro and biomass). More than that, DG consists of lower power generators connected directly to the distribution network or to the consumer [1].

The progressively larger dependency on RES can have significant impact in reducing carbon emissions. As mentioned, by producing closer to the consumption sites it is possible to minimize transmission losses, and by introducing the concept of prosumers and energy sharing it is possible to avoid grid congestion and consequent technical issues (voltage level stability) or large amounts of energy not-supplied (ENS). These technologies then enable lower electricity prices, fuel cost reduction and independence from large producers [32].

Despite several studies forecasting a full transition to renewable energy by 2050 [33], a study from 2017 suggest that in reality the steps required to do so are not being taken in time, placing the fault in the roughly 40% of all electricity being generated at coal-fired power plants (at the time) and the lag in the uptake of RES based generation [34][34]. When looking at Figure 2.1 we cannot say that there is a clear decrease in dependency from coal, but rather a lessening in an increase in dependency, as globally there is still an increase - just not as big an increase as the average from the last decade (4.5% yearly) [31].

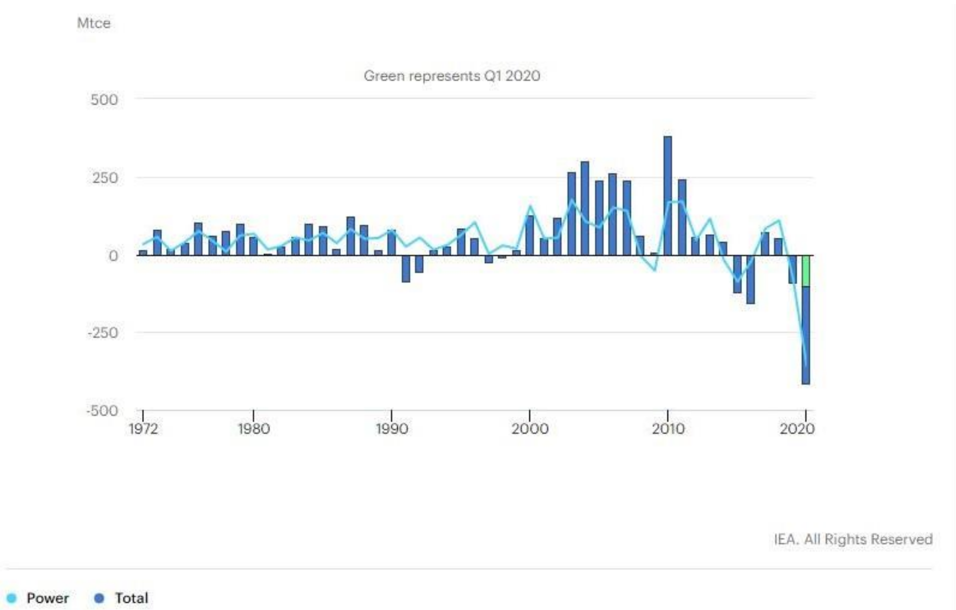

Figure 2.1 - Global annual change in coal demand, 1971-2020 [32].

Global coal demand grew by 0.7% in 2018 relative to the previous year as well. [31] associates this with the increase of its demand in Asia, outpacing the decrease everywhere else.

In the first quarter of 2020, coal consumption decreased 10% globally in reference to the first quarter of 2019 - the most severe drop since World War II (also due to the global pandemic and its impact on the economy) [35]. All in all, however, the role of coal in the global mix keeps declining, but perhaps too slowly, as it remains the largest source of electricity in the world. As Figure 2.2 indicates, during the 2020 COVID-19 pandemic all primary energy types' demand is projected to change negatively relative to 2019, with Renewables being the outlier [35].

Some doubt arise, then, as how to match these sustainability deadlines. Solutions could include [13]:

- New or improved technologies;
- Adhering to and popularizing the smart grid concept;
- Efficient data metering and communication;
- Improved energy management and energy storage.

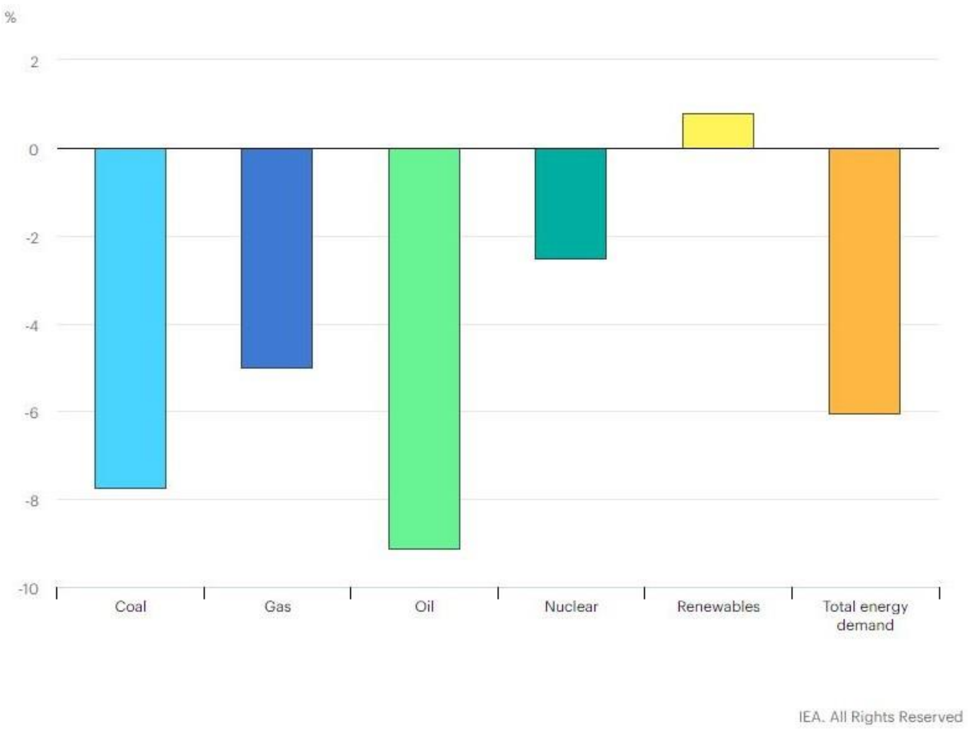

Figure 2.2 - Projected Change in Demand by Fuel for 2020 in respect to 2019 [36].

2.1.2 Global Goals and Legislation

In order to react to all the aforementioned environmental and development concerns, several governmental entities took action to steer the world's countries towards a more sustainable future. In this subsection a quick overview of some of the most relevant currently active legislation is done.

The European Union's climate action plan and the European Green Deal are the EU's way of fighting climate change by instating domestic policies and international partnerships [37].

In 2009, the 2020 climate energy package was instated, featuring three key targets [38]:

- 20% cut in greenhouse gas emissions from 1990 levels (e.g. by implementing the Emissions Trading System [39] and annual national emission reduction targets for several sectors)
- 20% of EU energy from renewables (e.g. national targets for renewable energy integration)
- 20% improvement in energy efficiency (e.g. through the NER300 program for renewable energy technologies and carbon capture storage; Horizon 2020 funding for research innovation; the Energy Efficiency Directive)

This package has different - more ambitious - iterations for 2030 (aiming to further cut emissions by at least 55% with reference to 1990 levels) [40] and for 2050 (aiming to become the world's first climate-neutral continent) [41]. Figure 2.3 illustrates the importance of the power sector in greenhouse gas emissions reduction and how it is ideally projected to vary, still while a continued growth of the economy is sustained [40].

However, these measures are not without implications and need of balance, as electricity prices rose significantly, especially in countries dependent on lignite and hard coal like Poland and Germany, as a consequence of the ETS. Some studies even suggest the implemented policies are not the most cost-effective [42]. These objectives are, however, frequently reviewed and discussed by the European Commission, being updated to match newer information and forecasts [43], showing the continuous concern and attentiveness to energy regarding environmental matters.

Internationally, approved by 196 United Nations Framework Convention on Climate Change Parties in 2015, [18] is historically one of the most important documents regarding environmental issues and international cooperation. Broadly put, it sets a global framework putting the world on track to limit global warming to below 2°C above pre-industrial levels, and aiming to become climate-neutral before the turn of the century through the implementation of 5-year cycles of increasingly ambitious climate action [44]. Before it was finally put in action in 2020, its predecessor was the well-known Kyoto Protocol, from 1997, that puts in operation the United Nations Framework Convention on Climate Change [45], [46]. Furthermore, most countries also have their own stance and objectives regarding climate change and their own legislation around energy.

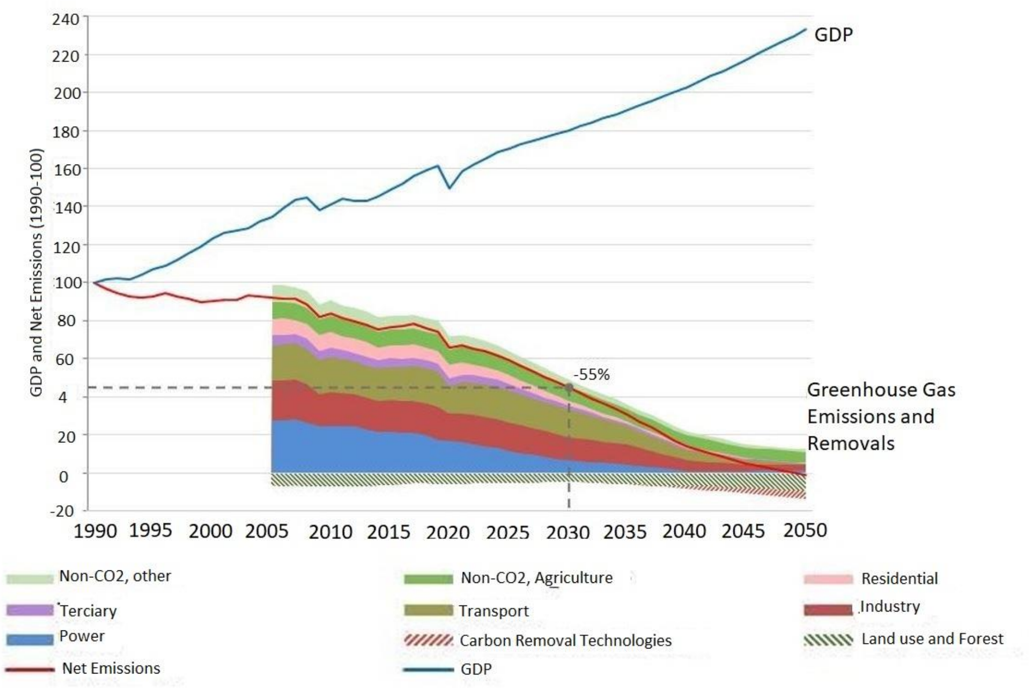

Figure 2.3 - GHG Emissions vs. GDP, 1990-2020, and forecasts until 2050 [47].

[48] analyses historic trends to enable energy policy makers to track their policy performance overtime and to compare them to others. It also reviews the initial impact of the

COVID-19 pandemic and traces regional energy profiles, rating them in three areas - energy security, energy equity and environmental sustainability. According to it, Central and Northern European countries rank among the best performers overall, and some Southeast Asian, Central American and African countries rank as the top improvers, from which Cambodia stands out. This Index is clear evidence of a recent global effort towards the same goals, while better ranked countries can be associated with growing and healthy economies.

Plans for bridging the gap between regions and the geographic limitations to RESs have been plentiful [49]:

- in 2003, trans-Mediterranean renewable energy cooperation, connecting Europe's wind power, North Africa's wind and solar and the solar of the Near East, solving the CO2 emission problem in Europe and socioeconomic problems in the other two regions;
- in 2006, a submarine transmission grid connecting all of Europe's surrounding seas;
- in 2007, the proposal of an integrated solar power plant and wind farm in the Sahara Desert that would transmit energy to Europe and Africa;
- in 2008, the North Seas Countries' Offshore Grid Initiative aimed to connect northern European countries' renewable plants and offshore wind farms;
- recently, the "Grid 2030" American plan to build a grid connecting Canada, the USA's east and west coast, and Mexico.

But they are nevertheless very big political and economic endeavors.

2.1.3 The Portuguese Context

Portugal is a member of the EU and a Party to the Paris Agreement, so it abides to the applicable international legislation and objectives control.

According to [50], Portugal's greenhouse gas emissions were 18.9% higher than in 1990, down from 46.2% in 2005, at which it reached its peak - while the European average stood at 76.7% of the value from 1990 in 2018. Portugal's share of renewable energy, as a percentage of gross final energy consumption, was 30.6% in 2019, higher than the 18.9% represented by the European average, both growing steadily since 2008 [50] (Table 2.1).

Among the EU countries, Portugal has the 5th most ambitious target for RES in final energy consumption under [51], at 31% by 2020. For context, other countries' national targets range from Malta's 10% to Sweden's 49%. Therefore, in 2019, Portugal was 98.7% towards its 2020 target. That said, about 60.2% of the energy produced in mainland Portugal is from renewable sources [52].

Figure 2.4 tells about Portugal's insufficient volume of energy production to satisfy the national demand and the dependency on imported fossil-fuels, as well as its significantly larger penetration of RES (60.2%) in respect to the percentage of RES in final energy consumption

(30.6%). This explains Portugal's carbon intensity staying much higher than the European average overtime, indicating there is still much space for developing new strategies towards a low-carbon economy.

The energy supply mix in Portugal per year is shown in Figures 2.4 and 2.5 [53]. In 2019, natural gas represented the biggest part of the mix, followed by wind. Solar was still a very small percentage of the mix. Overall, however, the percentage of renewable energy sources in the mix is very significant, with wind and hydro as the key sources.

Table 2.1 - Summary Table [49]

Greenhouse Gas Emissions, (%, base year 1990)		
	2005	2018
PT	146.22	118.9
EU (avg)	93.92	76.76
Share of renewable energy in gross final energy consumption (% of gross final energy consumption)		
	2008	2019
PT	378	30.619
EU (avg)	11	18.876

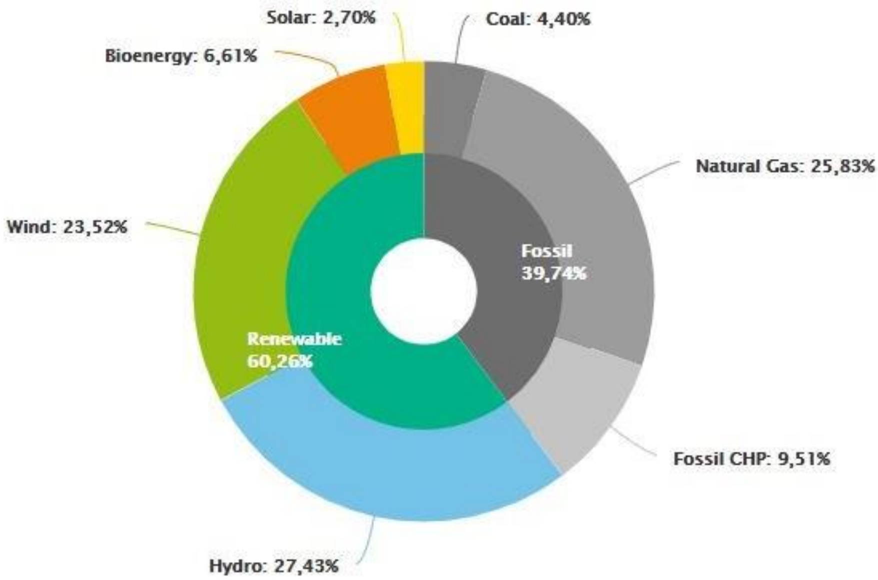

Figure 2.4 - Energy Mix in Mainland Portugal [54].

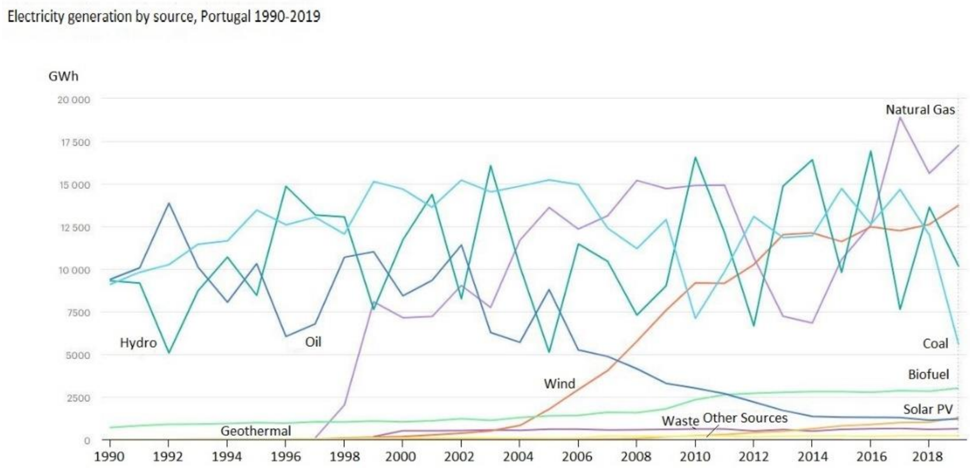

Figure 2.5 - Global annual change in coal demand, 1971-2020 [32].

In [55], Portugal updates previous legislation regarding climate action and energy, setting national goals to achieve between 2020 and 2030. Its key premises include:

- decarbonizing the national economy;
- prioritizing energy efficiency;
- prioritizing Renewable Energy and reducing the country's energy dependency (by promoting decentralized production and self-consumption);
- guaranteeing a just and safe energy transition.

In order to achieve this, among other important measures, it:

- eliminates the tax exemption of coal for electricity production and other subsidies;
- sets out to tap into resources such as offshore wind and wave power;
- foresees the phase-out of coal from the energy production mix, by shutting down Portugal's last two plants - Sines and Pego;
- sets natural gas up as the system backup to ensure a feasible transition;
- capacity auctions for solar energy;
- sets out to value renewable gas resources such as hydrogen;
- promises the promotion of decentralization and self-consumption of energy;
- reiterates the importance of the smart grid concept and intelligent metering and communication systems.

To achieve this, [56] and [55] were released. This document is transposed from an European directive. This means the goals were set at European level, but the means to achieve them are set at a national level, and are described in this document. Most importantly, it:

- sets the goal of at least 80% RES participation in electricity production, as to achieve a 47% quota of renewables in the final consumption of energy;
- legally formalizes the concept of Renewable Energy Communities (REC) for the first time, setting the prosumers rights to participate in a REC, where they are able to produce, consume, store and sell renewable energy through bilateral renewable electricity contracts;
- estimates the need for 1 GW of solar decentralized capacity by 2030;
- reiterates the importance of the complementarity between decentralized energy production and centralized tools to boost clean energy such as capacity auctions (this should contribute to social and territorial cohesion, diminishing inequality);
- boosts competitiveness in the electricity market, facilitating the active participation of companies and citizens who are interested in investing in distributed generation that will supply their own needs, without public subsidies.

2.1.4 RESs-based DG Integration

RES-based Dispersed Generation Integration implies the notion of injecting energy back into the grid, in a direction the original technology was not built to support. This brings into discussion several new technical challenges.

2.1.4.1 Technical Challenges

Although they are an important part of decarbonization and future energy generation, big scale integration of decentralized RESs comes with technical challenges for the system operation, since the traditional network is not prepared to receive technology of these characteristics.

Furthermore, until now, predictable and easily manageable fossil fuel based production was used to cover for the flexibility issues derived from the unpredictable RESs. With decarbonization as an objective, this will not be possible in the future. Particularly, quality and stability problems arise from [1]:

- high volatility renewable energy increases system requirements for balancing supply and demand (meaning flexibility problems, with the weather conditions dictating possible and unpredictable sharp ramp variations in production in just milliseconds);
- the need for bi-directional power flow (which the traditional passive grid was not designed for);
- higher system frequency oscillations from;

- the need to redesign the protection system;

To minimize the impact of these limitations [57]:

- planning studies must be done before construction in order to comprehend the risks and options posed;
- increased flexibility - curtailment levels and reserve requirements - is a necessity;
- investments in monitoring and communication systems are crucial.

The complete evolution to smart grids (active grids instead of the traditional, passive grids) should mitigate these challenges, despite there still being issues to be solved before that is possible [29]. However, behavioral, political and economic factors are also a major challenges not to be forgotten, as theoretically speaking, every technical issue could be solved with sufficient funds and time.

2.1.4.2 RESs Integration – Current World Position

Fueled by policy support and the progressively lower cost of solar PV and wind power technology, RES-based DG has grown significantly as of recent. The electricity sector remains the center of attention regarding green energy, but it only accounts for one fifth of global energy consumption, with transportation and heating remaining critical focus points in the energy transition [32]. Global penetration of RESs sat at 27% in 2019 [32] - far from the objective of 50% by 2030 (Figure 2.6).

This value is hard to increase since, despite increasing RES-based generation, it cannot be expected that developing countries would give up coal and other fossil-fuel-based energy production in a short amount of time, given the harsh economic impact - so even though RESs capacity increases, it also increases for non-RESs. For a forecast of renewable capacity growth between 2019-2024 per source, refer to Figure 2.7.

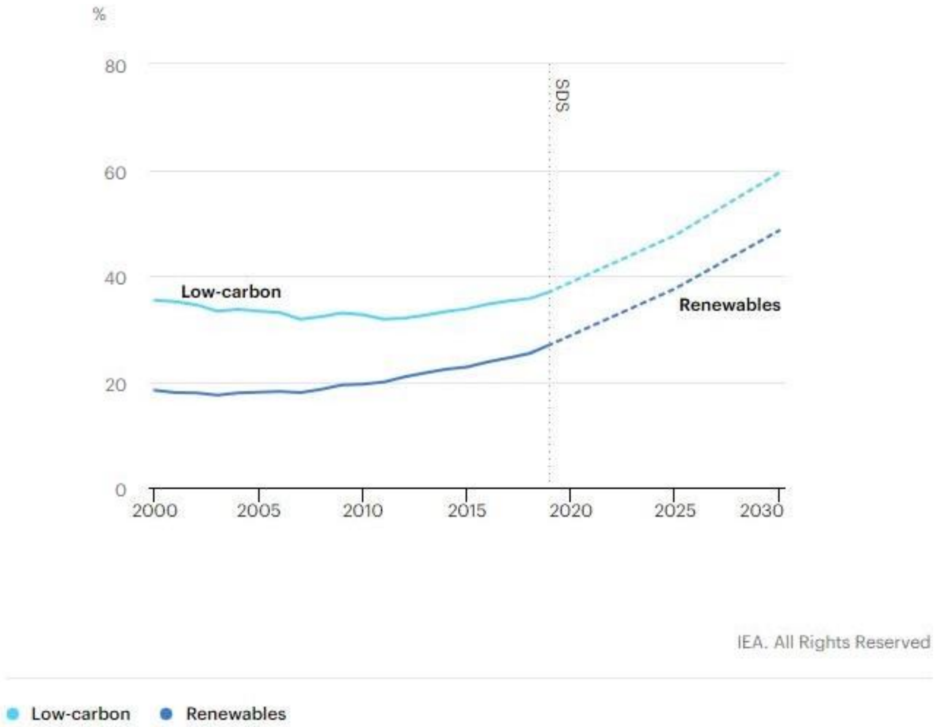

Figure 2.6 - Share of renewables in power generation in the Sustainable Development Scenario, 2000-2030 [33]

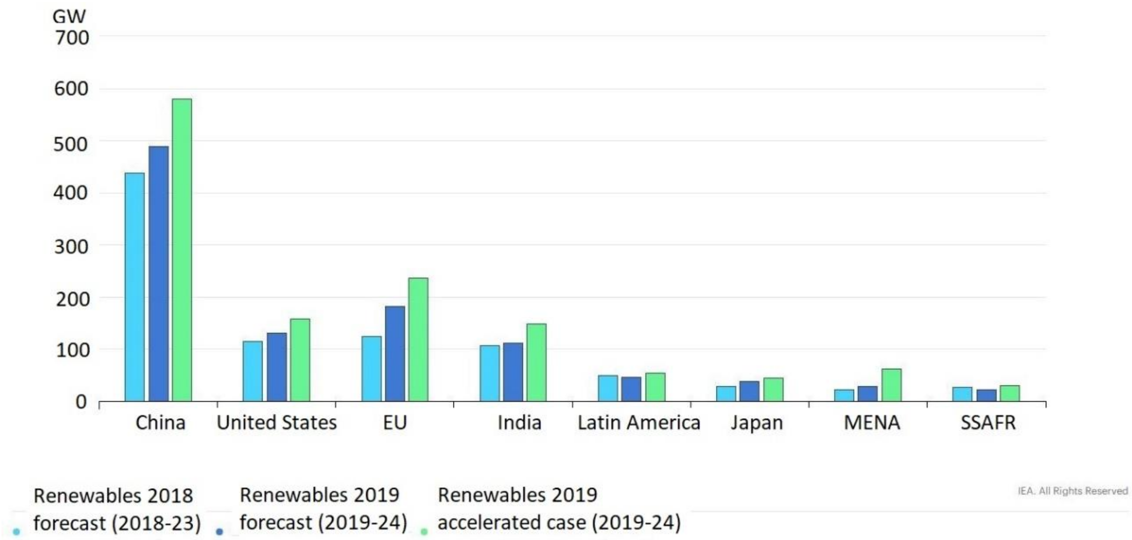

Figure 2.7 - Renewable capacity growth by country/region, 2018-2024 [33].

Growth is projected to be particularly large for solar PV and wind power [33], as expected. Particularly for solar PV, Figure distributes the installed (or projected) capacity per country/region. In the projected scenario, China represents about 40% of global capacity (Figure 2.8).

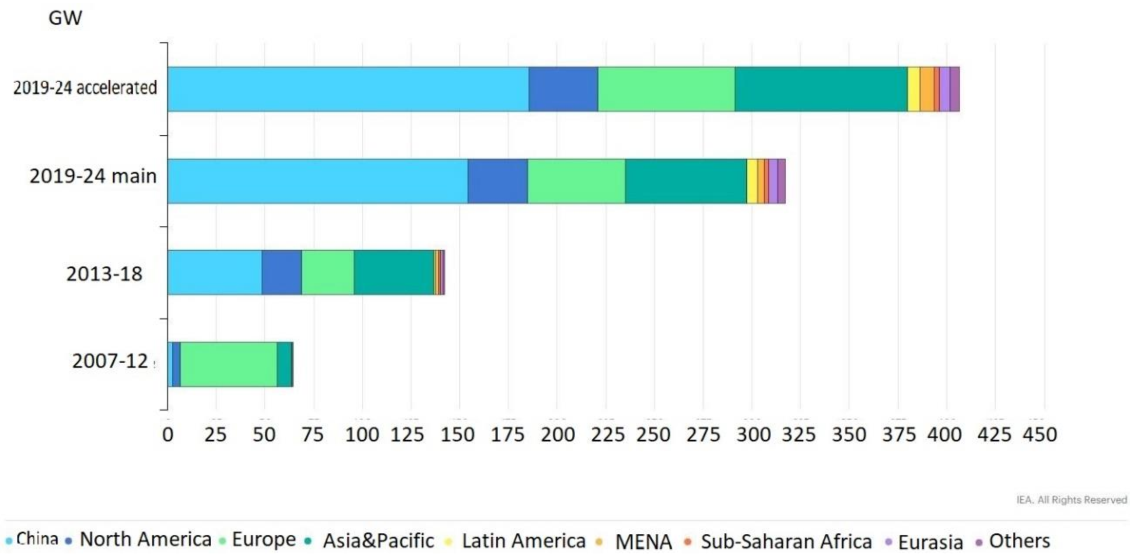

Figure 2.8 - Distributed solar PV capacity growth by country/region [34].

2.1.4.3 Energy Storage Systems (ESSs)

Electricity storage is set to play a key role in the near future as a facilitator for the energy transition, for its ability to compliment RES-based energy generation, helping to somewhat counter their variability. It should also have a big impact by accelerating the feasibility of off-grid electrification and directly decarbonizing the transport sector, playing a central role in EV deployment.

ESSs can have a lot of different applications. A summary of some of the most relevant ones is represented in Figure 2.9 [58]. From these, electric energy time shift (150,34 GW) is by far the most common, followed by electric supply capacity (7.18 GW), black start (6.29 GW), renewables capacity firming (5.68 GW) and spinning (2.18 GW).

Speeding up the transition may not be as simple as deploying large volumes of storage though. This technology still has a ways to go before being widely available as a cheap technology. How it is perceived will depend on storage cost and performance. Germany, for instance, relies on other options like electricity trade with neighboring countries, flexible power plants or demand-side management [58]. The relevance of ESSs as an alternative therefore depends on the sector, application, availability and how other solutions weigh against it in each situation.

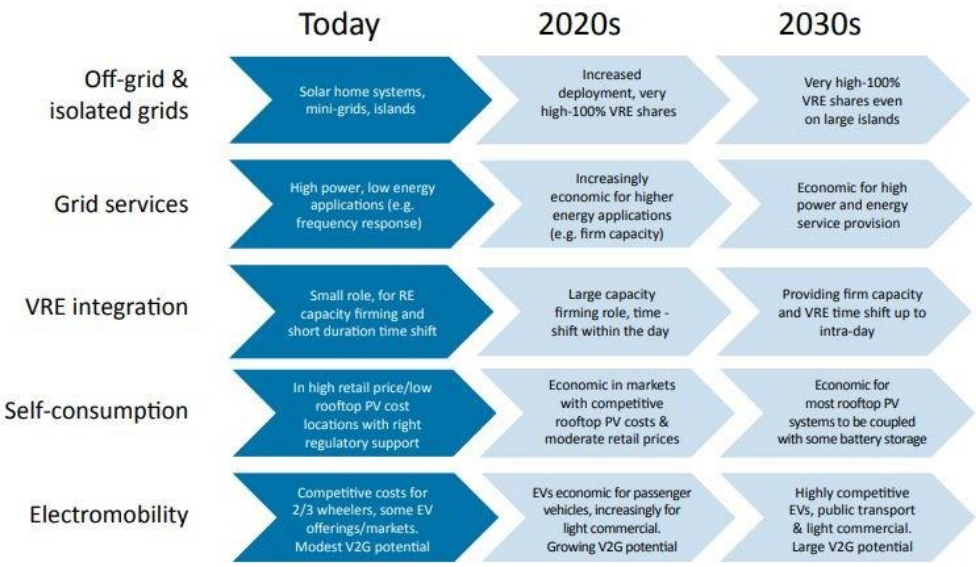

Figure 2.9 - Electricity storage needs in the energy transition [55].

2.1.4.4 ESSs - Technology, Operation and Challenges

There are various types of energy storage technologies, from which Thermal Energy Storage is by far the most deployed globally [59]. Pumped hydro storage is the largest contributor to storage deployment at the moment. Renewable energy-specific applications account for almost half (49%) of all main capacity applications. China, Japan and the United States of America make up roughly half of the world’s pumped hydro storage capacity [57] (Figure 2.10).

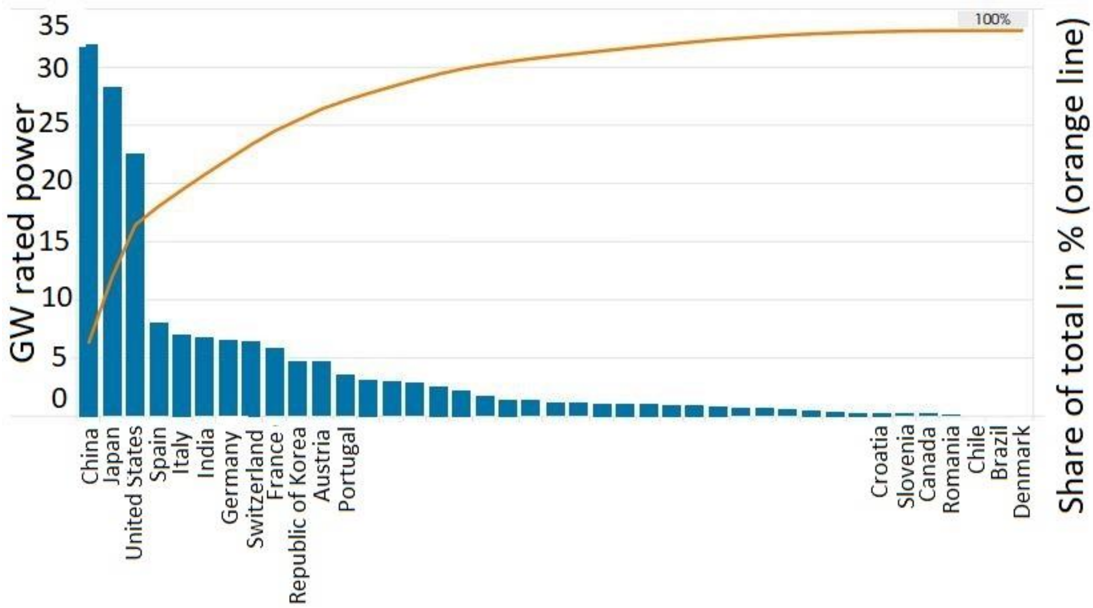

Figure 2.10 - Global operational pumped hydro storage power capacity by country, mid-2017 [55].

Thermal energy storage applications include - maybe most relevant to the present paper - providing the flexibility to dispatch electricity outside of peak sunshine hours. Smaller, yet growing, applications include small PV owners. Germany and Australia have been in the front of this market, in an attempt to increase self-consumption. Electro-chemical storage (i.e. EV batteries) is an exponentially growing market, despite representing a very small portion of deployed capacity in 2017 at 1.9 GW. Despite not being the sole technology being used, Li-ion batteries represented the lion share of operational installed capacity in 2017 (59%). Other technologies include high-temperature sodium-sulphur batteries, capacitors and flow batteries.

In Japan, the Republic of Korea and the United States of America, utility-scale projects in the MW scale dominated deployment in 2017. In Germany though, policies encouraging DG fueled behind-the-meter deployment of small-scale storage. This follows a global exponential growth in battery storage deployment, as seen in Figure 2.11 [60].

Batteries respond very rapidly to load changes and accept co-generated or third-party power, contributing to the system's stability. It is common for batteries to have minimal standby losses and high energy efficiency (60% to 95%). Li-ion batteries have 100% energy conversion, making them a favorable option, but are expensive [13]. Electrochemical storage units are compared based on specific energy per weight and rate of charging. Other relevant concepts include state of charge and depth of charge. This technology allows to generate power at low voltage and low power ratings, as well as to flatten the load curve, explaining why it is such an attractive technology. Of course, charging during off-peak hours and supplying during peak hours can help this.

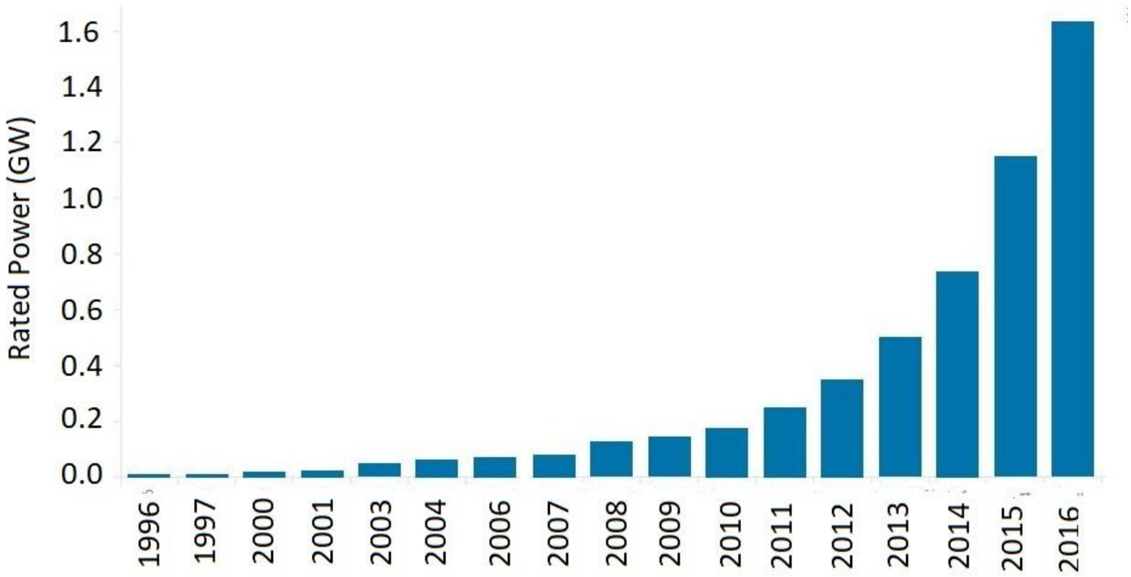

Figure 2.11 - Global electro-chemical storage capacity, 1996-2016 [55].

2.1.4.5 ESSs Integration - Current World Position

In an unprecedented turn, global annual installations of energy storage technologies fell around 20% (for grid-scale storage) in 2019, after increasing steadily for almost a decade. Behind-the-meter (typically residential level) storage "remained flat overall despite a near-doubling of residential batteries, consolidating a shift towards behind-the-meter storage" [61]. This source associates this change with uncertainties around battery safety. Figure 2.12 represents annual energy storage deployment per country/region, and highlights the fickleness of this market, as it varies dramatically depending on policy changes.

Impacted by the 2020 crisis, these values are likely to follow the same trend going into the following year, as battery production has a particularly complex supply chain. Scandals in the Korean media and changing policies in Japan made Japan the market leader in a single year, once more underlining how subject to rapid change this market is - a characteristic of an early-stage technology [60].

On the other hand, [58] predicts a sizeable increase in deployment by 2040, with India and China leading the way (Figure 2.13), namely using this technology in the same location as renewable energy production facilities in a supportive role, in order to stabilize supply. In [57], storage capacity should be at 1000 GW by 2030 - 600 GW being from EVs, 325 GW from pumped hydro and the rest from stationary battery storage. For comparison purposes, solar and wind installed capacity should reach 5 times that value by the same time. By 2050 we are expected to see total storage capacity reach 3000 GW, with EVs accounting for most of the total [57].

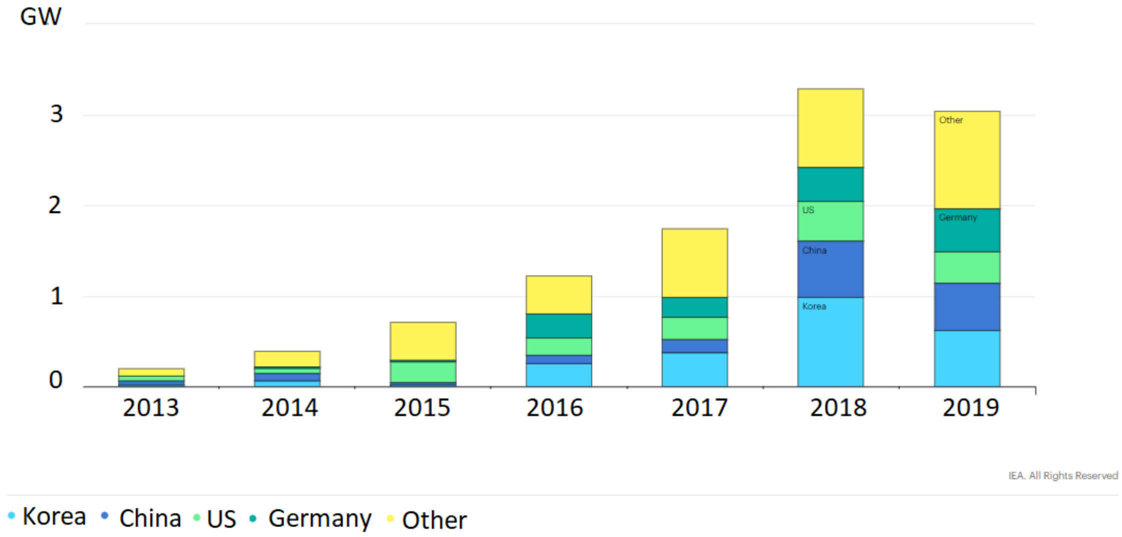

Figure 2.12 - Installed capacity of utility-scale battery storage systems in the New Policies Scenario, 2020-2040 [56].

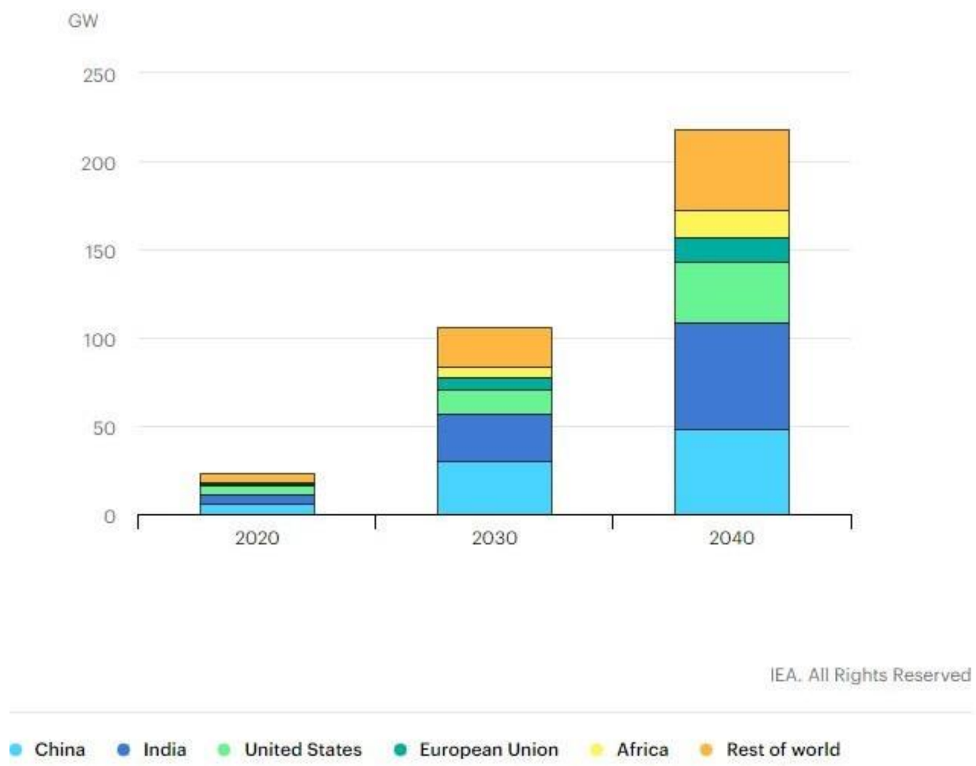

Figure 2.13 - Installed capacity of utility-scale battery storage systems in the New Policies Scenario, 2020-2040 [56].

2.2 - Energy Markets and Energy Trading

In this subsection, notions related to energy markets and energy trading are presented - specifically how RES integrate energy markets, what energy sharing and energy communities are, and examples of existing projects of P2P energy trading business models. System Modeling is also discussed.

2.2.1 A Brief Introduction

Electricity as a commodity has to be treated differently from others, given that [62]:

- Electricity cannot be stored economically nor for sufficiently long periods of time (yet);
- The flow of electricity is physically impossible to control easily and efficiently while respecting safe flow limits and without safety or failure risk;
- Demand varies per time unit and generation has to be matched with it at all times, creating a flexibility problem, as some resources vary sharply and in an unpredictable way, while others only allow for a very slow output change and have big start up times and costs.

This makes electricity an extremely complicated commodity to price, as it varies in time and space up until it's delivery in real-time. As [56] says, "Electricity is not only energy in MWh; transmission capacity and flexibility are scarce resources and should be priced accordingly", not to mention energy quality.

Due to this, it is advantageous to create different energy markets to draw the bridge between producers and consumers of electricity. For example, in Europe, there are energy markets engulfing several countries such as the MIBEL and Nordpool, but also a market for individual countries such as in Great Britain and Italy. France and Germany, Belgium and the Netherlands (central western electricity market CWE).

The timeline for energy trading in these markets spans four years prior to the delivery time of electricity [63]-[65]:

- Further from the delivery date, long-term markets are used. At this time, bilateral contracts (over the counter or OTC deals) can be established to trade electricity at an agree volume and price. Prices are called by bidding zone, which generally overlaps with national borders (though not necessarily).

- Closer to the delivery date, although there is no obligation to participate, spot markets (day-ahead or intraday markets) can be used to adjust long-term deals. It is to be expected, then, that the volumes traded here are much smaller than in the long-term market. The day-ahead market is a pan-European auction held every day and concerning the following 24 hours. Selling and buying bids are cross-matched, and the point of intersection dictates the marginal price, which is the price paid for all accepted bids. After the day-ahead market is cleared, the intraday market opens. This market depends on the country, but it is either treated in a similar manner as stock exchange, or auctions are held.

- After the intraday market closes, balancing markets deal with balancing supply and demand in real-time. To do this, there are year-long contracts to buy the availability of providers. When needed, these providers can be called upon to help maintain the balance, ensuring there is always enough energy available to satisfy the demand.

- Often times the dispatched outcome of the markets can violate the operational limits of transmission networks, so there is a need for a "transmission re-dispatch", ensuring generators do not overload potentially congested lines. For this end, the output of said generators are increased or decreased, and their owners are financially compensated.

2.2.2 RES in Energy Markets

Energy Markets generally deal with RES-based energy differently than energy fueled by more pollutant sources. This is, once again, caused by the intrinsic stochastic characteristic of RESs and environmental concerns. Subsidies are generally given to energy production using endogenous or renewable sources and processes with great efficiency (i.e. cogeneration), although definitions vary from country to country and market to market [66]. As these technologies are usually prioritized by means of insertion at zero cost in the offer curve of the market, producers are almost sure to sell all they produce. Low risk is another mechanism for enticing investors for these types of production, and more volume of this type of energy being traded signals a trend for lower energy prices [67].

2.2.3 Energy Sharing and Energy Communities

Initially, in Europe, the energy sector (the production, transmission, distribution and trading of electricity) has been a natural monopoly. However, as time went by, steps towards the reality we know today were taken, starting with the separation of each of those components and their regulation. At first, transmission and distribution stayed a monopoly, while energy trading was transformed into a competitive market through a slow, gradual process. Ever since 2008, most EU countries have a liberalized market for electricity, despite the wide variety of differences in regulatory framework in the different markets, specifically regarding price regulation and consumer protection. In the future, the EU is working with the goal of a unified energy market in mind, removing technical and administrative barriers in order to achieve the set low-carbon economy goals [68].

The switching rate is a key indicator in evaluating the competitive development of an electricity retail market. It indicates the share of households who changed their supplier of electricity, or that changed their tariff with the same supplier. High switching rates may be considered an indicator of strong competition and of consumers' choice awareness. "In general, countries that still have retail price regulation have a lower number of active suppliers as well as a lower switching rate compared to countries with fully deregulated retail prices" [69]. This implies that the higher degree of liberalization a country has, the more active and competitive the market. [69] also suggests the person's level of education and life habits could influence the strength of the market, as people like the elder would be discouraged from switching given the choice, perceiving regulated prices as "safer", given their legacy. [70] also supports this as it states that "Well-functioning retail markets require the involvement of consumers in market activities", and that "this involvement mainly refers to supplier switching. It depends on many factors such as easy switching processes, consumers being aware of their opportunities and of the rights and tools that can empower them to participate."

Figure 2.14 [71] shows that most countries in the EU have had a relatively high (over 10%) external (between different suppliers) switching rate, with most of them reporting a higher number in 2018 than the average from 2013-2017, reflecting the impact of the market liberalization on a positive growth in competitive development in energy retail markets.

A competitive market is important when aiming for a goal such as the UN's seventh goal - "affordable and clean energy for everyone" [72]. In this context, with a progressively higher degree of liberalization throughout, individuals started to be able to participate independently in the market, further raising competitiveness. This concept goes hand in hand with the notion of self-sustainability and both producing and consuming your own energy.

Going one step further, it could be considered natural viewing not only ourselves but our neighbors as suitable suppliers of electricity - tapping into the concept of energy sharing and energy communities. Energy could be generated locally and shared at lower prices than the market offers, mitigating several issues in the process, such as network strain and transmission losses. Because local generation is usually RES-based, it would also mean promoting clean energy alternatives and a low-carbon energy sector.

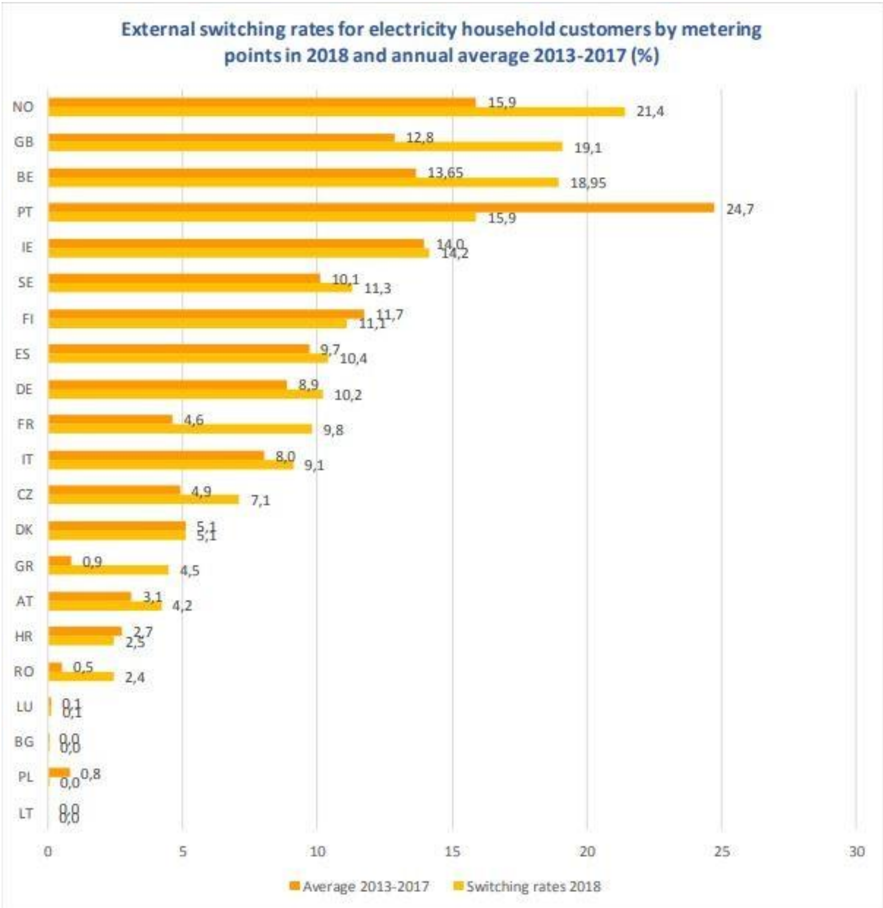

Figure 2.14 - Switching rates for electricity household customers in 2018 and annual average 2013- 2017 (%; by metering points) for selected countries [67].

2.2.4 P2P Business Models Regarding Energy Trading

There are three different market structures proposed for P2P trading [23]:

- Full P2P market - agents (any active or passive market participant) freely negotiate directly between each other, agreeing on transactions without centralized supervision;
- Community-Based P2P market - a centralized agent supervises transactions between agents within a community;
- Hybrid P2P market - members of P2P market energy communities can also negotiate with other communities.

This new philosophy not only economically benefits the customer but also the environment, since it promotes the increase of the penetration level of renewables. Moreover, this new paradigm is aided by the use of storage units - needed due to the unpredictable nature of the renewable energy resources. They enable a prosumer to storage the surplus generation and use it when needed. However, there is still a challenge to overcome, which is that customers owning local production or storage units still need to be connected to the grid for reliable electricity service, and technical problems arise with sufficient RES penetration as long as the network does not finish the transition to the smart grid, as mentioned before. This paradigm change also carry some downsides, such as the fact that as more customers go off-grid, the cost of the grid infrastructure will be divided among a lower number of customers which will lead to higher electricity bills, namely on what concerns the use of grid tariff components. Besides that, off-grid customers will probably suffer from a low reliability of energy supply in a long-term period. Furthermore, the respective charging/discharging of storage units decline their life duration, which lead to further investment costs, which are already high [73].

Existing P2P Trading Projects include Piclo (UK), Vanderbron (NL), PeerEnergyCloud (DE), Smart Watts (DE), Yeloha (USA), Sonnen Community (DE), Lichtblick Swarm Energy (DE), Community First! Village (USA), Dajie (UK) and Hive Power (CH). More in depth information on these projects can be found in [68].

2.3 – Bibliographic Revision in System Modeling

Regarding the specific theme of this paper, it is possible to find other works that address system modeling problems in energy. All of the examples discussed in this section use MAS based modeling in some way, as does the present paper. However, in spite of also using MAS modeling, it differs from other papers by tackling P2P energy transactions in a smart grid environment. This means its scope is not limited to a microgrid environment, but can also be applied to one. How- ever, it is important to highlight that the present paper focuses on the economic point of view of the matter - the proof of concept, in comparison to more traditional alternatives - instead of focusing on technical feasibility, which is more widely discussed.

Regarding the technical aspect, it is common to see a focus on voltage restoration and control, regarding self-sustainability as a key objective. It should not come as a surprise, considering that in most cases a microgrid environment is considered. Naturally, a lot of them also discuss the incorporation of RESs and ESSs in order to help flatten the demand curve. Differences between these works mostly lie on how they approach the modeling. [74] highlights the use of distributed controllers instead of a central controller; [73] suggests a two-layered approach to multi-microgrids, by optimizing the management of a single microgrid, and then the optimization of the cluster, maximizing the use of ESSs; [75] deals with microgrid clusters, and suggests dividing them into smaller "sub-microgrids" and optimizing each of those more simple systems in order to improve dynamic performance.

An economic point of view should see its focus turn towards the end user experience - financial operation and modeling depending on end user behavior and preferences. As [76] puts it: "our focus is on the improvement of community energy status, while traditionally research focused on reducing losses due to transmission and storage, or achieving economic gains" - as it prioritizes achieving a zero energy community, in which (by definition) a neighborhood achieves null net balance of energy use and RES-based generation; although sharing demand and capacity information should prove necessary in order to balance any system, [77] exposes the concerns of creating a susceptible environment without privacy in the presence of P2P energy arbitrage; [26] explores how an electric storage unit and an electric power generator interdependence varies depending on the degree of their exposure to the environment, relying on MASs and distributed Reinforcement Learning; [27] revolves around a demand side management strategy that takes advantage of different consumption and production profiles in a neighborhood to shift peak loads and minimize electricity costs;

It is possible to see that, regarding this theme, research is mostly dedicated towards a specific need or concern, while leaving the broader subject of P2P energy trading to any adequate means of simulation. With this paper a broader view is proposed, setting out to prove this concept in any smart grid environment, without such limitations as the high investment costs of these technologies, the heavy presence of ESSs (an early-stage technology), the variable policies surrounding EVs and (by using MASs modeling) scalability issues. With this, the intention is that this paper will serve a purpose as indication that even without very radical transformation in our present reality, it is possible to welcome this concept and to put it to work, not being exclusive to microgrids or new grids or neighborhoods with extremely high financial possibilities. [15] makes a very similar approach, exploiting "generation/demand flexibility from an energy community perspective", and using agent-based modeling in order to simulate social interactions and end-user behavior - arguably the most defining trait of this subject. Going one step further, [78] introduces non-residential members in a community environment similar to that of [15], with a similar objective. Also worth mentioning is [11], that not only evaluates its results based on demand-side flexibility and its impact on electricity costs but also end-user' dissatisfaction, or comfortability - a relevant part of the practical popularization of this concept in the future.

2.4 - Chapter Summary

The state of the art is present in this chapter and is divided into three parts. The first part addresses renewable energy sources and their part in the energy transition. This chapter also links this to the global goals and the legislation put in place to achieve them. The Portuguese context is mentioned in particular and compared to the EU average values for different parameters of relevance and EU goals, as an example. Still in this part, RESs-based DGs integration and energy storage systems are discussed, including technical challenges and current world standing.

In the second part, a brief introduction to energy markets and energy trading is made to provide context to RESs - stochastic sources with very significant storage challenges - in energy markets. To help illustrate the novelty of this discussion, a few examples of market structures for P2P trading and existing P2P trading projects is provided.

Finally, the third part presents a bibliographic revision on systems modeling, where the contributions of other works are discussed, as well as how they tackled the discussion, and interesting standout features of some of them to take into account.

Chapter 3

Tools and Conditions

In the following chapter the Anylogic software if discussed. An overview of how the model was constructed is also provided, including settings, environment and assumptions.

3.1 – The Anylogic Software

The AnyLogic simulation software was developed in 2000 and supports agent based, discrete event, and system dynamics modelling or a combination of these three [79]. It has been used in diverse settings, including in the energy system [15]. The software is based in Java and allows users to extend models using Java. AnyLogic has a high degree of flexibility which allows the user to fully capture the complexity of the agents' interactions at various levels of details [80]. Importantly, the software allows for communication between agents which is important as the agents can transmit information regarding their status and preferences [79].

AnyLogic is well suited for the modelling of dynamic systems. These systems are characterized by non-linear behavior, agent memory, non-intuitive interactions between agents and variables, and time and causal dependencies [81]. In addition, these systems generally consist of a large number of agents and various forms of uncertainty.

Anylogic has a graphic environment with programmable blocks. In this model, a population type agent ("people") was placed inside the main environment ("main"). In the upper level ("main") code affects the entirety of the model and runs before entering the lower level ("people"). In the lower level, code affects each agent individually in a successive manner, although interaction between agents has to be coded differently. Each function and event parameter can be individually coded and customized; events can be timed to activate other code blocks; agents, connections and even environments can be customized to set actions and code for individual agents or functions; among other particular useful resources (Figure 3.1).

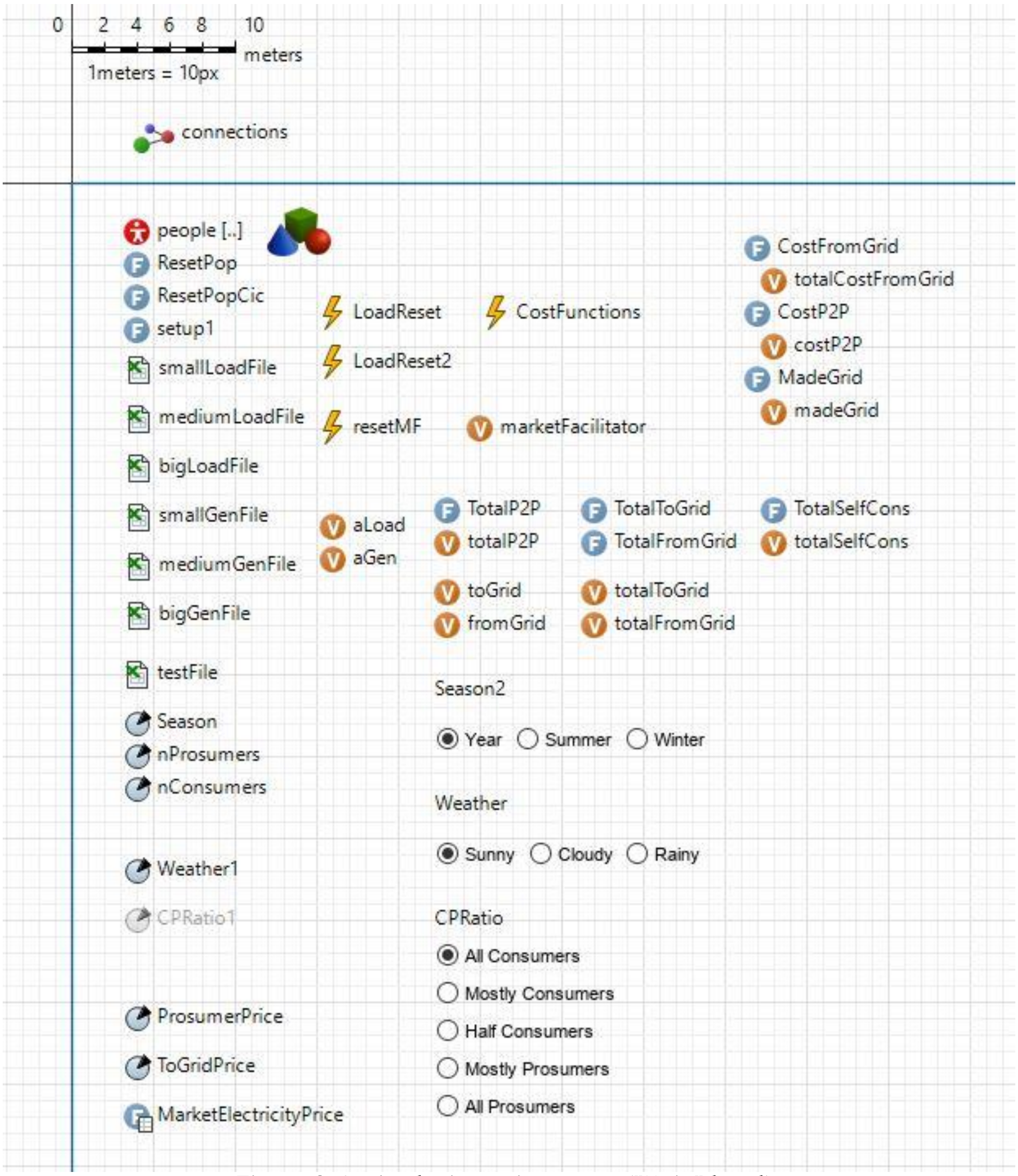

Figure 3.1 - Anylogic environment ("Main" level).

An example of the code used in the model can be seen in the figures below. Figure 3.2 shows Java code from a function in the “main” environment referring to agents in the “people” population; Figure 3.3 shows the parameters of a block used to associate values given from the upper environment to an environment contained by it (“people”); Figure 3.4 and 3.5 show code from inside the “people” environment that runs for each agent independently, but affects community related variables in upper levels of the software.

```
double x = 0.1;
int xe = (int) x;

while(x<(nProsumers*0.113)){
    for(int col=2   ; col<26    ; col++   ){
        //getCellNumericValue(int sheetIndex, int rowIndex, int columnIndex)    //bL bG
        aLoad.values[col-2] = bigLoadFile.getCellNumericValue(Season, 1, col);
        aGen.values[col-2] = bigGenFile.getCellNumericValue(Weather1, 1, col);
    }

    Person person = add_people();
    people(xe).goToPopulation(people);
    setup1(aLoad, aGen, people(xe));

    people(xe).IniVal();

    x++;
}

while(x<(nProsumers*0.1431)){
    for(int col=2   ; col<26    ; col++   ){
        //getCellNumericValue(int sheetIndex, int rowIndex, int columnIndex)    //bL medG
        aLoad.values[col-2] = bigLoadFile.getCellNumericValue(Season, 1, col);
        aGen.values[col-2] = mediumGenFile.getCellNumericValue(Weather1, 1, col);
    }

    Person person = add_people();
    people(xe).goToPopulation(people);
    setup1(aLoad, aGen, people(xe));

    people(xe).IniVal();

    x++;
}
while(x<(nProsumers*0.1506)){
    for(int col=2   ; col<26    ; col++   ){
        //getCellNumericValue(int sheetIndex, int rowIndex, int columnIndex)    //bL sG
        aLoad.values[col-2] = bigLoadFile.getCellNumericValue(Season, 1, col);
        aGen.values[col-2] = smallGenFile.getCellNumericValue(Weather1, 1, col);
    }

    Person person = add_people();
    people(xe).goToPopulation(people);
    setup1(aLoad, aGen, people(xe));

    people(xe).IniVal();

    x++;
}
```

Figure 3.2 - Anylogic Code example 1

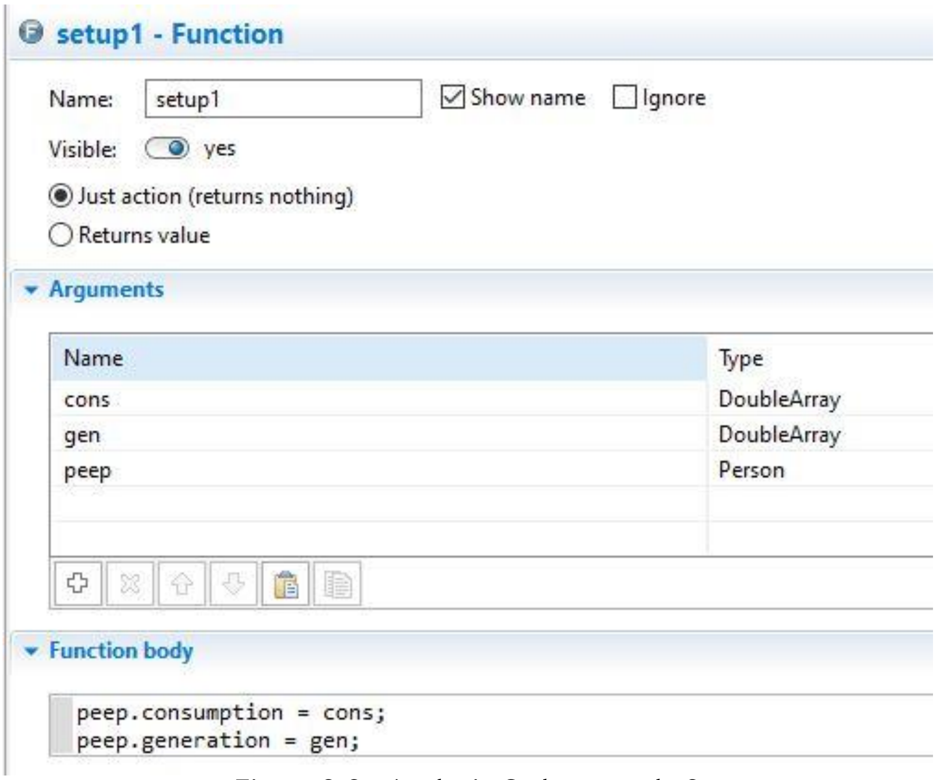

Figure 3.3 - Anylogic Code example 2

```java
for(int j=0; j<24; j++){
    main.marketFacilitator.addSelfCons(Math.min(generation.values[j],consumption.values[j]), j);
    main.marketFacilitator.addIniLoad(consumption.values[j], j);
    main.marketFacilitator.addIniGen(generation.values[j], j);
    }

System.out.println("selfconssomado[0]:" + main.marketFacilitator.selfcons[0]);
selfconscheck = Math.min(consumption.values[getHourOfDay()] , generation.values[getHourOfDay()]);
System.out.println("selfconscheck:" + selfconscheck);
```

Figure 3.4 - Anylogic Code example 3

```java
int hour = getHourOfDay();
System.out.println("INITIALIZE SC :" + hour );

main.marketFacilitator.addBalance((consumption.values[hour] - generation.values[hour]), hour);
System.out.println("cons pre sc:" + consumption.values[hour]);
System.out.println("gen pre sc:" + generation.values[hour]);

if(main.marketFacilitator.balance[hour] > 0){
    main.marketFacilitator.addConsumption(main.marketFacilitator.balance[hour], hour);}
else if(main.marketFacilitator.balance[hour] < 0){
    main.marketFacilitator.addGeneration(Math.abs(main.marketFacilitator.balance[hour]), hour);}
else{main.marketFacilitator.addConsumption(main.marketFacilitator.balance[hour], hour);
       main.marketFacilitator.addGeneration(main.marketFacilitator.balance[hour], hour);}

System.out.println("consumed pos sc:" + main.marketFacilitator.consumed[hour]);
System.out.println("generated pos sc:" + main.marketFacilitator.generated[hour]);

main.marketFacilitator.addBalance2((main.marketFacilitator.consumed[hour] - main.marketFacilitator.generated[hour]), hour);

if(main.marketFacilitator.balance2[hour] > 0){
    main.fromGrid.values[hour] = main.marketFacilitator.balance2[hour];}
else if(main.marketFacilitator.balance2[hour] < 0){
    main.toGrid.values[hour] = Math.abs(main.marketFacilitator.balance2[hour]);}
else{main.fromGrid.values[hour] = main.marketFacilitator.balance2[hour];
     main.toGrid.values[hour] = main.marketFacilitator.balance2[hour];}
```

Figure 3.5 - Anylogic Code example 4

Of course, Anylogic being a Java based software, it would be impossible not to think of classes as a major part of coding in Anylogic. In Figure 3.6 an example is shown.

MarketFacilitator.java

```java
/**
 * MarketFacilitator
 */
public class MarketFacilitator implements Serializable {

     double consumed[] = new double[24];
     double generated[] = new double[24];
     double balance[] = new double[24];
     double iniload[] = new double[24];
     double inigen[] = new double[24];
     double selfcons[] = new double[24];
     double balance2[] = new double[24];


    /**
     * Default constructor
     */
    public MarketFacilitator() {
    }

    @Override
    public String toString() {
        return
                "consumed = " + Arrays.toString(consumed) ;
    }

    public synchronized void addConsumption(double quantity, int hour) {
        this.consumed[hour] += quantity;

    }

    public synchronized void addGeneration(double quantity, int hour) {
        this.generated[hour] += quantity;
    }

    public synchronized void addBalance(double quantity, int hour) {
        this.balance[hour] = quantity;
    }
```

Figure 3.6 - Example of a Java Class

3.2 Case Study

The coded model is comprised of a virtual population of 100 agents. Each agent has independent variables for load and generation profiles, unique per percentage of the population according to Table 3.3 and explained in detail below. All agents are randomly placed in a virtual environment and are connected to each other, which enables them to participate in energy transactions with each other. Note that although agents are randomly distributed by the software, they are placed in the same place in every simulation, allowing for consistent analysis.

The simulation is run for 24 hours - each time in varying conditions - in order to make a sensitivity and cost analysis. The varying inputs are seasonality and weather (which impact the load and generation profiles), and the percentage of prosumers in the mix of agents.

Generation values depend solely on the PV panels' production. There is no other type of energy production considered.

The market energy price was taken from [83] which presents a similar concept to the present one and is presented in Figure 3.7. The price for selling energy to the grid is set at 90% of the hourly price of the market, in accordance with [86], and the price for P2P transactions at 45% of the hourly price of the market according to [87].

The load values are yearly and seasonal (summer and winter) averages, aggregated per hour and the number of people living in each household, calculated from datasets from [82]. This database includes data from more than 1000 locations in the United States for at least 12 years. This ensures the data is not influenced by events such as droughts, financial crisis or others like microclimates or unique cultures, and is as generic as possible. This will allow the model to be applied to more cases in the future. Table 3.1 contains the value corresponding to the size of the household (agent) depending on the number of people living in it.

The generation values are also yearly averages, aggregated per hour. These are, in turn, defined by the size of the house – assuming the bigger the house, the more PV panels could be installed. Table 3.2 contains the value corresponding to the PV panels' individual capacity depending on the weather.

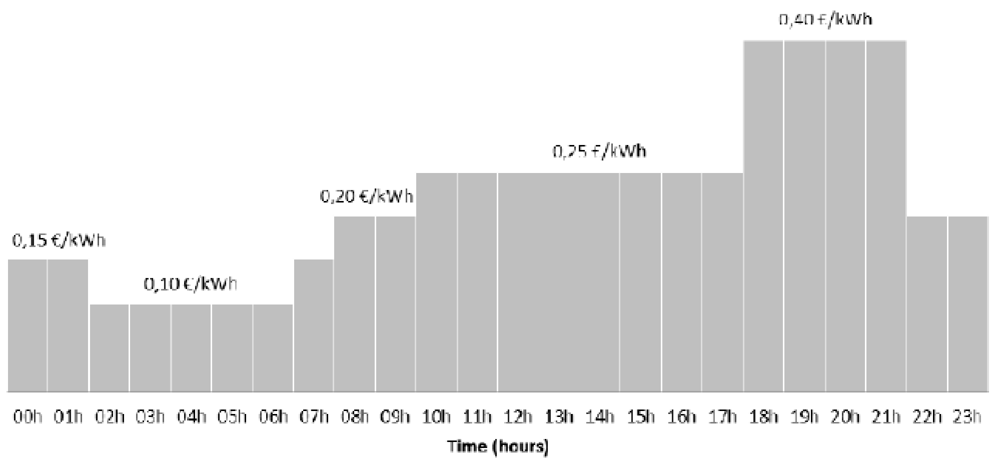

Figure 3.7 - Market Energy Prices per Hour

Table 3.1 - Number of Persons per House (Agent) Affecting Load Profiles.

Number of Persons	
Small	1-2
Medium	3

Big	4+

The number of people living in a house does not have a scientific correlation to the size of the house. In order to distribute the agents' profiles as close to reality as possible, values from Table 3.3 were taken [83].

Storage, electric vehicles and shiftable loads were not taken into account in this model. The model prioritizes self-sufficiency and independence from the grid. As such, all agents prioritize self-consumption above all else. If self-generated energy is not sufficient for the hour (keeping in mind there is no storage and values are hourly averages) or the agent is a consumer, it will move on to P2P transactions. As all agents have different living conditions (reflected in different load and generation profiles) even if one has no surplus, there may be one who does. After self-consumption, all agents communicate with the Market Facilitator and it associates the agents with surplus with the agents with load to be supplied, so they can enter in P2P transactions. Finally, if there is surplus after all agents' loads for the hour are supplied, it is sold to the grid; or if there is load to be supplied after all agents' surplus has been used, energy is bought from the grid. This process repeats itself every hour.

Table 1.2 - Weather Type Affecting Generation Profiles

Weather and Corresponding PV panel capacity (kWp)	
Sunny	2
Cloudy	1.5
Rainy	1

Table 3.3 - Distribution (%) of Agent Profiles per Size of House and Number of Persons Living in them

Size of Household	Number of Persons Living in Household	Corresponding % of Population
Big	4+	0,1130
Big	3	0,0301
Big	1-2	0,0075
Medium	4+	0,0551
Medium	3	0,1654
Medium	1-2	0,0441
Small	3	0,0314

Small	1-2	0,5533

3.3 - Chapter Summary

In this chapter the Anylogic software was discussed. A brief introduction to ABM was provided and how it applies well to a concept such as P2P Energy trading. Some code examples were shown to underline the level of customization possible with this software. The constructed model is discussed in detail, including justification for the chosen values and inputs in the calculations such as market prices, load profiles and distribution of agents in the environment, as well as all of the assumptions made.

Chapter 4

Case Study, Results and Discussion

The fourth chapter of this dissertation describes all the simulations considered, the results from each of them and some analysis on the results. Finally, a cost analysis is made comparing all of the simulated cases.

4.1 Baseline

Establishing a basis for comparison, the most common case for a generic neighborhood was selected - a population made of 100% consumers. This, of course, implies 0% prosumers - no local generation of energy, no self-sufficiency, no peer-to-peer transactions, and total dependency from the grid. In this case, the weather had no impact on the input given the breadth of the acquired data for the demand and the lack of generation. A yearly average was selected for the load values to avoid higher or lower demands (summer or winter months) and remain as generic as possible.

In this base case, the 100 consumers consumed a total of 4070 kWh during the 24 hours (Table 4.1) and there is no self-consumption or P2P trades. The energy mix of the consumers is shown in Figure 4.1. It can be seen that the load is completely satisfied by importing energy from the grid.

As expected, in a scenario with only consumers, there is only the hourly load profile ("Load") that overlaps with the energy bought from the grid ("FromGrid"). At every point in time, given that there is no generation, all agents have to buy their energy directly from the grid. This is a good opportunity to observe the demand curve, where very high demand can be seen at the later hours of the day. This is relevant for the model since no significant energy production from PV panels can be expected at those times and there is no way to shift the load nor storage the energy.

Table 4.1 - Baseline Results

Base Case (kW)	
P2P trades	0
Self-Consumption	0
From Grid	4070,556
To Grid	0
Load Supplied	4070,556

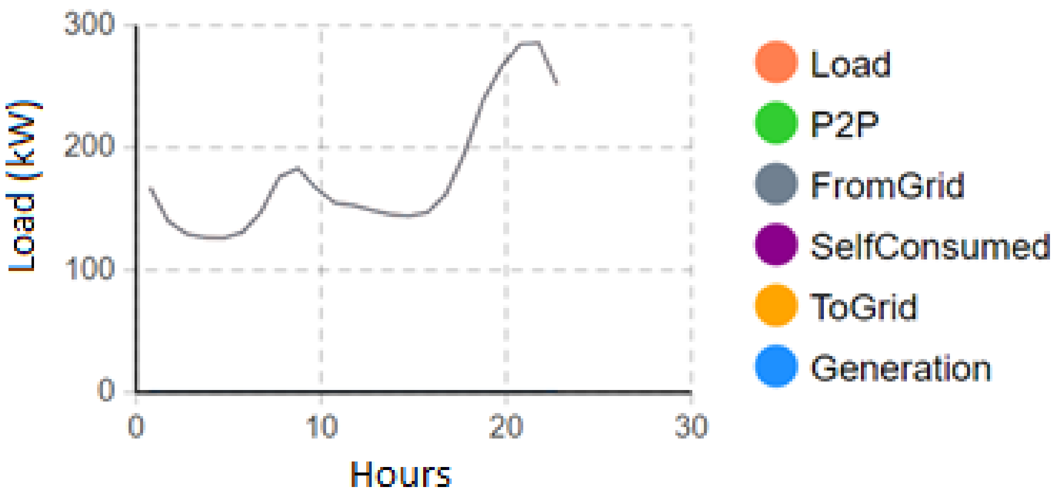

Figure 4.1 - Energy balance of the baseline with no prosumers.

4.2 Case 1 - Altering the Penetration of Prosumers

Case 1 incorporates prosumers into the mix of agents in different ratios to analyze their contribution to the validation of the model. Starting with 25%, then 50%, 75% and 100%, local generation is increasingly brought into the mix and enables self-consumption and P2P transactions. It stands to reason that the higher the penetration of locally produced RESs, the more self-sustainable and independent the microgrid will be. With this model in place, costs should also lower. Of course, this will only be applicable when there is local generation, so there should be a noticeable difference when the natural resources allow it to be. This does mean that we should still witness a considerable amount being purchased from the grid.

Here, seasonality and the weather will impact the inputs but the parameters remained unchanged to not affect the analysis. The load values were yearly averages and the weather was "Sunny".

According to Figure 4.2, as generation starts to increase because of PV panels during the day, the necessity to buy from the grid decreases accordingly. During these hours, because of the priorities established by the model, there is also an increase in self-consumption and P2P transactions. There is not a significant amount of generation with this configuration, and the dependency from the grid stays at 87% (Figure 4.3). The total load supplied stayed roughly the same from the base case. The amount of energy imported from the grid is reduced during the day due to self-generation. No conclusions referring to the linearity of the impact of prosumer penetration on the growth of self-consumption and P2P trades can be drawn yet. There was no surplus, so there was no export of energy to the grid (Table 4.2).

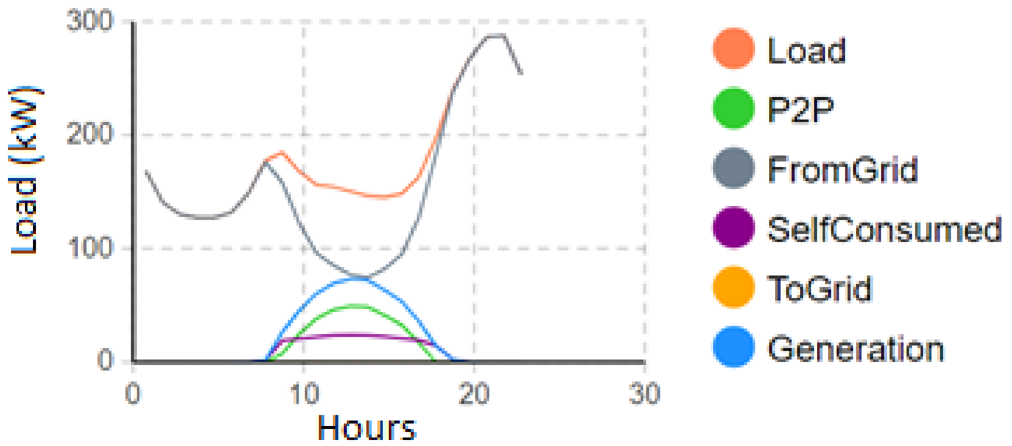

Figure 4.2 - Energy balance with 25% prosumer penetration.

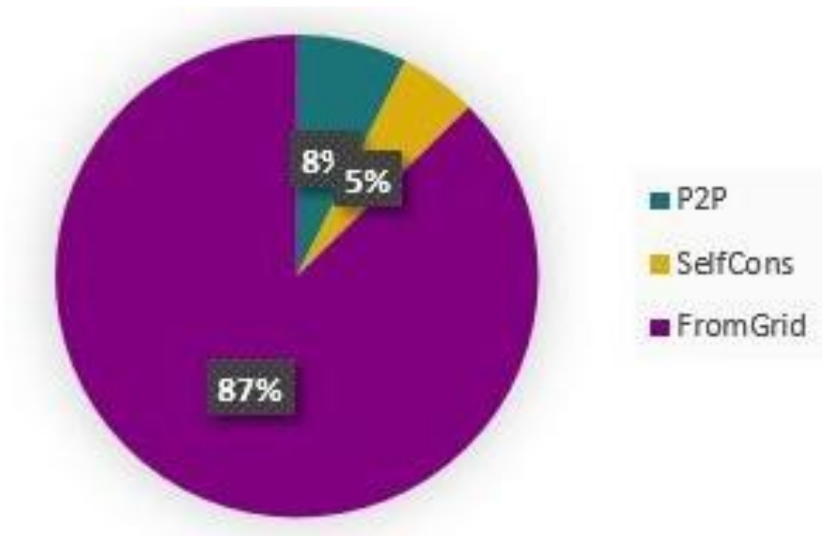

Figure 4.3 - Total energy balance with 25% prosumer penetration

As seen in Figure 4.4, for the first time there is enough surplus to have energy sold to the grid, even if in minor quantities (Table 4.3). There is a decrease of 13% of dependency from the grid, with total demand satisfied by self-consumption and P2P having doubled from the previous simulation. There is more generation and self-consumption compared to the previous scenario (Figure 4.5). Self-consumption grew linearly in comparison to the previous simulation, while P2P Trades saw a larger increase.

Table 4.2 - Case 1 25% Prosumers Results

Case 1 25% Prosumer Penetration (kW)	
P2P Trades	305,309
Self-Consumption	212,773
From Grid	3582,581
To Grid	0
Load Supplied	4100,663

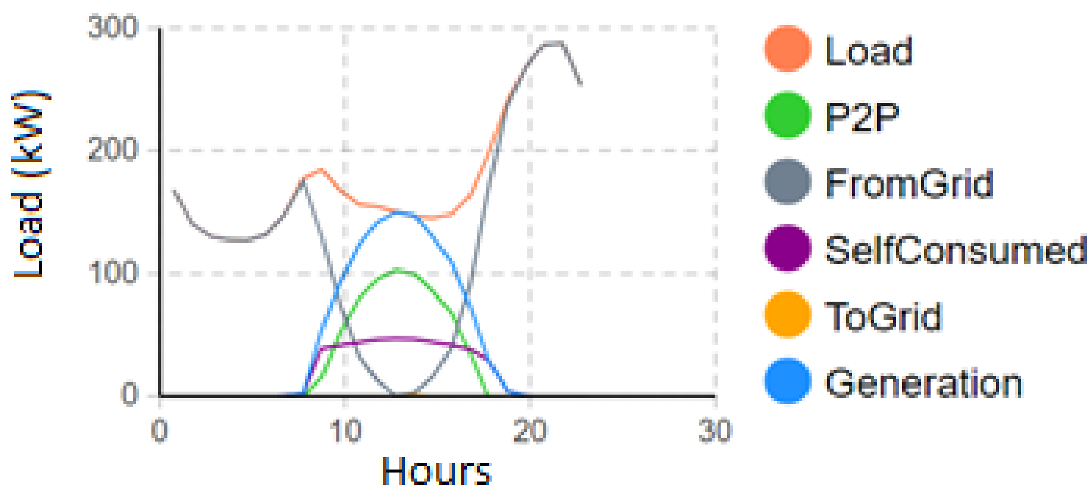

Figure 4.4 - Energy balance with 50% prosumer penetration.

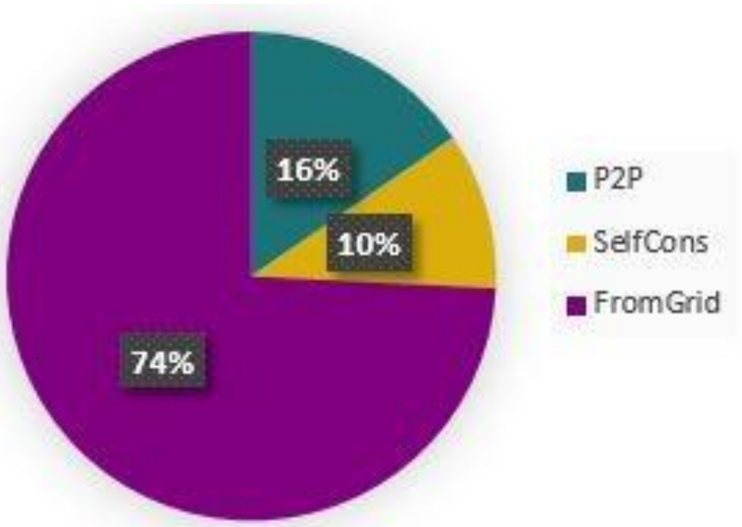

Figure 4.5 - Total energy balance with 50% prosumer penetration.

Table 4.3 - Case 1 50% Prosumers Results

Case 1 50% Prosumer Penetration (kW)	
P2P Trades	633,11
Self-Consumption	425,215
From Grid	3045,104
To Grid	0,96
Load Supplied	4103,429

Referring to Figure 4.6, during peak generation hours, generation exceeds the load profile. This leads to a lot more energy being exported (sold) to the grid at those hours, earning the prosumers revenue. Curiously, P2P transactions stagnate at the same percentage of the last simulation (16% load) and are even lower at peak generation hours. The population is completely self-sufficient from around 11 am to 4 pm, buying no energy from the grid. Self-consumption continues to increase significantly, although at a lower rate (from 10% to 15%) – see Figure 4.7. Dependency from the grid thus decreases by 5% more. Table 4.4 shows that self-consumption continues to increase linearly with prosumer penetration, while P2P trades showed little increase (less than 1% of the energy mix).

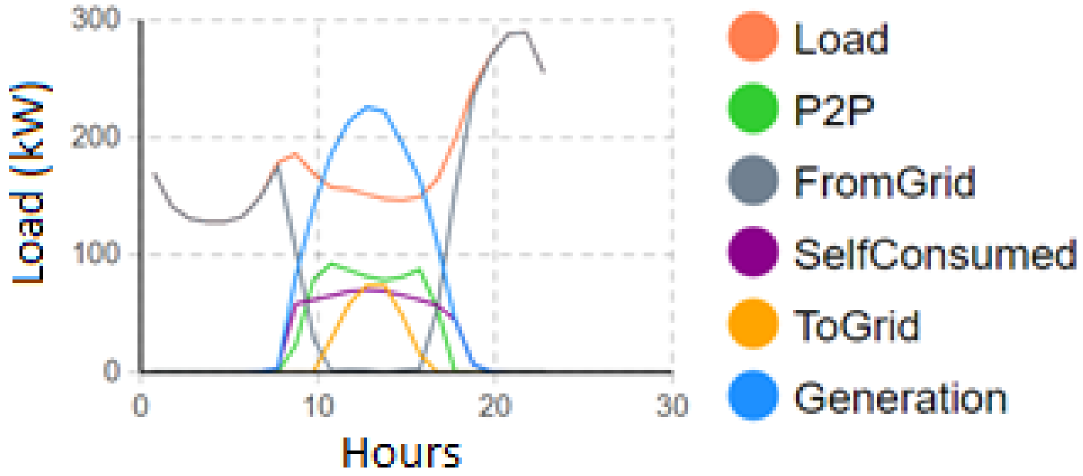

Figure 4.6 - Energy balance with 75% prosumer penetration.

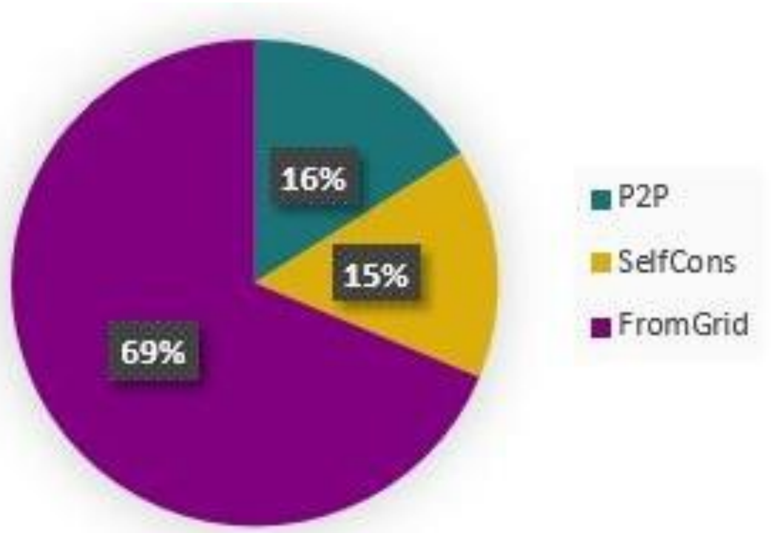

Figure 4.7 - Total energy balance with 75% prosumer penetration.

Table 4.4 - Case 1 75% Prosumers Results.

Case 1 75% Prosumer Penetration (kW)	
P2P Trades	663,825
Self-Consumption	633,203
From Grid	2843,08
To Grid	298,578
Load Supplied	4140,108

Finally, following Figure 4.9 most trends can be observed to continue, with self-consumption increasing by another 6% and dependency from the grid decreasing by 3%. However, energy traded in P2P transactions decreases (from 16% to 13%), particularly during peak generation hours. Energy is not bought from the grid from 10 am until around 6 pm (Figure 4.8). Of course, there is a major increase in energy sold to the grid (Table 4.5). Self-consumption continues its linear increase with the increasing penetration of prosumers in the community and dependency from the grid (energy taken from the grid) is the lowest of all scenarios at roughly 2693 kW (66%).

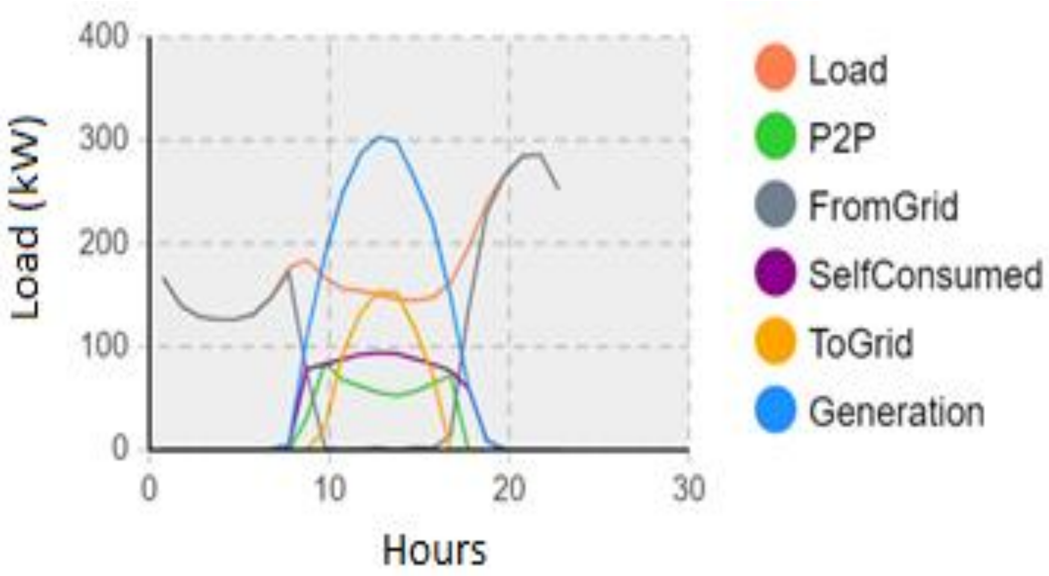

Figure 4.8 - Energy balance with 100% prosumer penetration.

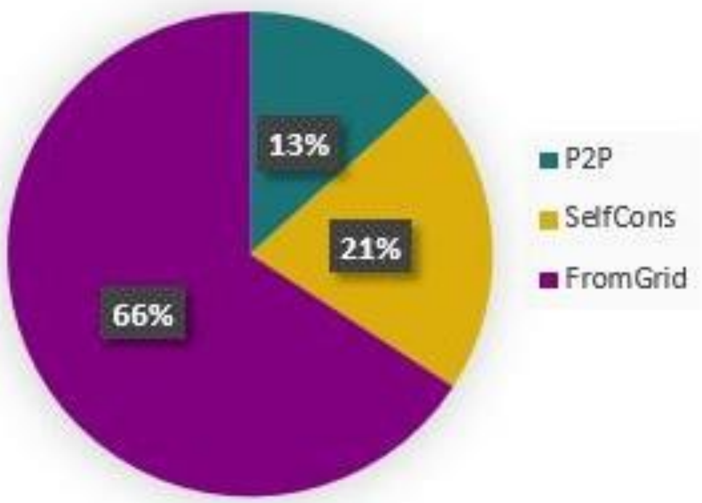

Figure 4.9 - Total energy balance with 100% prosumer penetration.

Table 4.5 - Case 1 100% Prosumers Results.

Case 1 100% Prosumer Penetration (kW)	
P2P Trades	546,649
Self-Consumption	852,891
From Grid	2692,91
To Grid	744,516
Load Supplied	4092,45

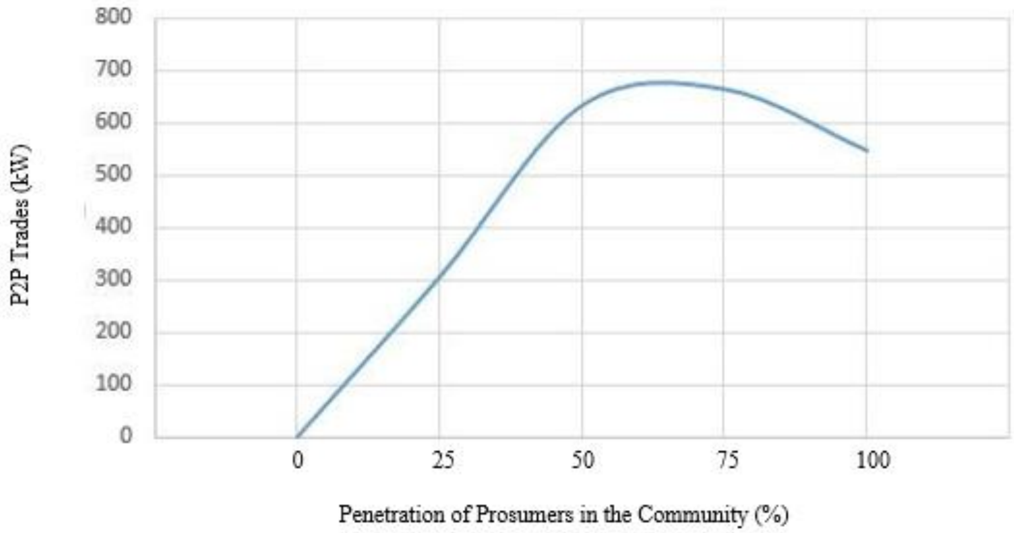

Figure 4.10 - Energy traded in P2P transactions in each of the 5 previous simulations.

Figure 4.10 shows that P2P trading is not linear. There should be a balance between prosumers and consumers to optimize energy trading. With only consumers, there is naturally no trading. As more prosumers are introduced, more energy is traded until a peak is reached, around the value that there starts to be surplus (generation starts to equal or exceed demand at some points in time). As more prosumers with similar profiles are introduced, the profiles stay the same but with higher values, and the energy being traded starts to decrease (although, as noted before, self-consumption continues to increase greatly and steadily).

Thus, the highest percentage of P2P energy trading in these conditions would likely be with somewhere between 50 to 75% of prosumers. That balance is where the model would reach most success. Nevertheless, 25% prosumer presence already had considerable impact and could be a reasonable starting point. 75% prosumer presence was the best scenario analysis. After this point, the mode’s efficiency decreased. Also, the scalability of this model should not be a problem, this being another advantage of only using PV panels. It should work in any neighborhood scale as long as the distribution of the agents is not highly unfavorable, in which case transmission losses could come into the discussion.

4.3 Case 2 - Effect of Weather

Case 2 builds on Case 1 (50% prosumers) and analyses the impact of seasonality and weather in the results. The “Sunny Summer” simulation uses hourly averages of the months corresponding to the summer as demand input. The load to be supplied is much lower than the yearly average, but the generation values stay the same, it being a "sunny summer". According to Figure 4.11, this scenario has the highest percentage of load supplied by P2P transactions yet with 17%, while keeping dependency from the grid at 70%. There is a considerable surplus at peak generation hours. The population maintains some degree of self-sufficiency during the hours of daylight, with a considerable surplus during peak generation hours (Figure 4.12). The exact values for this scenario can be seen in Table 4.6. It is important to note that the total load to be supplied is much lower than the average load in subchapter 4.6, at 2764 kW compared to the previous 4103 kW (50% prosumer penetration).

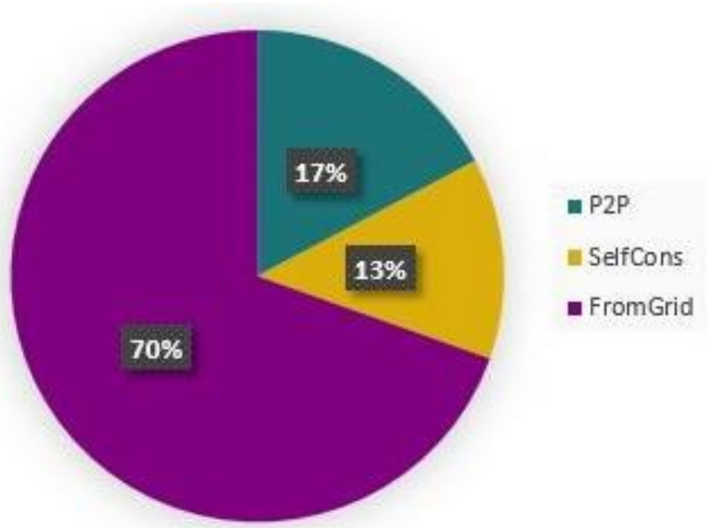

Figure 4.11 - "Sunny Summer" Total Energy mix.

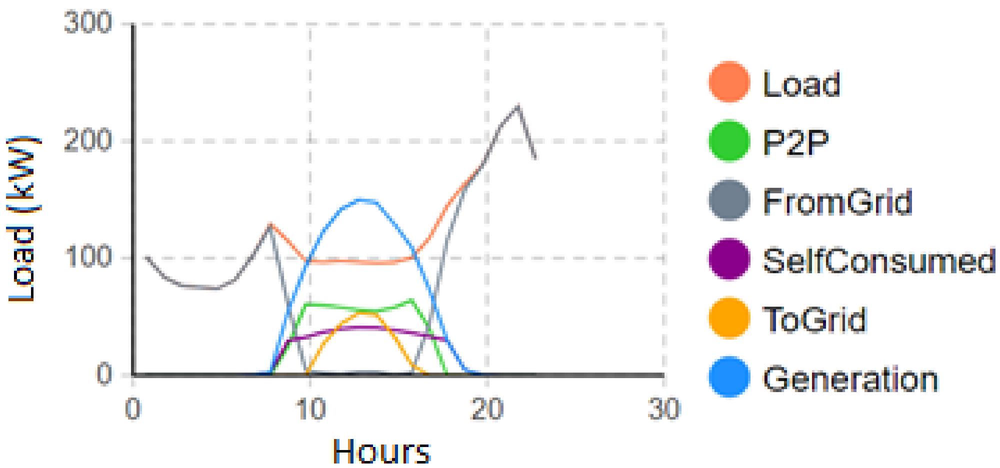

Figure 4.12 - “Sunny Summer” energy mix.

Table 4.6 – "Sunny Summer" Results.

"Sunny Summer" Results Simulation (kW)	
P2P Trades	476,227
Self-Consumption	365,252
From Grid	1922,872
To Grid	217,807
Load Supplied	2764,351

The "Cloudy Summer" simulation builds on the last one, testing the impact of the weather on the results. It is a "cloudy summer" simulation. As generation decreases with the loss of natural resources (daylight for PV panels), the model naturally loses efficiency as generation depends solely on PV panels' generation. Despite this, the results are still somewhat successful. In regards to the last simulation, according to Figure 4.13, dependency from the grid increased by 7% as the load supplied by both P2P transactions and self-consumption decreased. There is no surplus, and no energy being sold to the grid. At no point in time is the population completely self-sufficient (Figures 4.14 and Table 4.7). This shows that weather has a great influence on P2P transactions since they are partly dependent on the excess generation at any given time. The summer season means the total load supplied stayed roughly the same (Table 4.7), but the decrease in local generation because of the cloudy weather means a decrease in self-consumption and P2P trading which in turn means more energy bought from the grid.

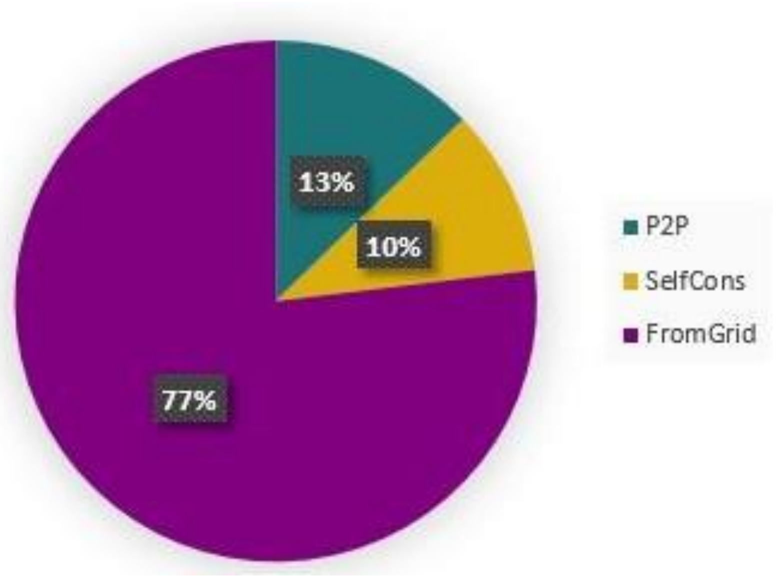

Figure 4.13 - "Cloudy Summer" total energy mix.

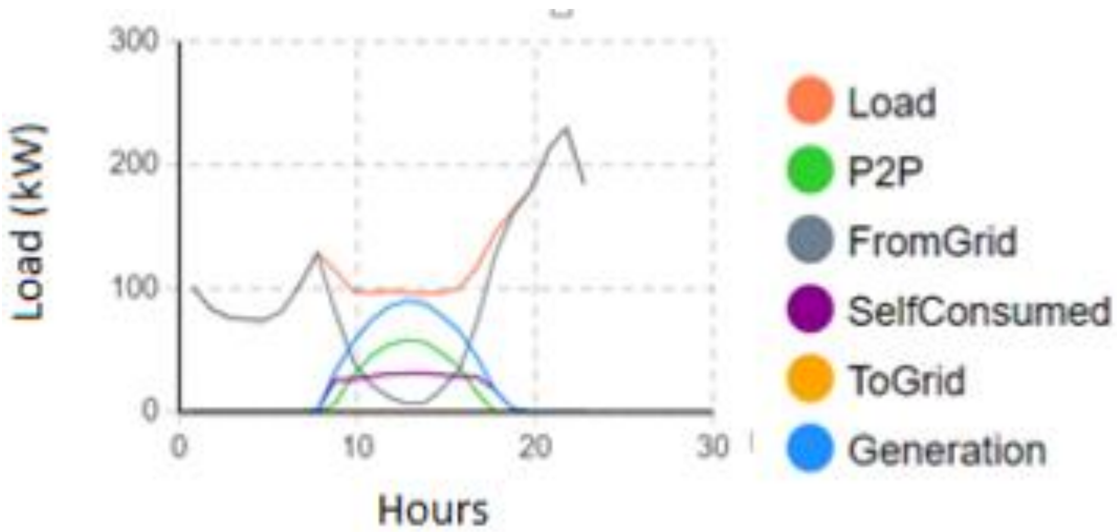

Figure 4.14 - "Cloudy Summer" energy mix.

Table 4.7 - “Cloudy Summer” Results.

“Cloudy Summer” Simulation Results (kW)	
P2P Trades	350,575
Self-Consumption	284,996
From Grid	2117,204
To Grid	0
Load Supplied	2752,775

The “Cloudy Winter” simulation uses hourly averages of the months corresponding to the winter as demand input. The load to be supplied is much higher than the yearly average (Table 4.8), and the local generation values are the same as in the last simulation, it is a cloudy weather simulation. Dependency on the grid increases greatly (from 70% and 77% in the summer scenarios to 88%), as the lower amount of generation is insufficient to satisfy a sizeable portion of the higher demand (Figure 4.15). Nevertheless, there are still some P2P transactions (4% of the energy supplied). Figure 4.16 shows the curve of energy imported from the grid nearing the load curve, which is to be expected when all other ways to satisfy demand decreased greatly and are only present during daylight hours (PV panels’ production).

Table 4.8 - "Cloudy Winter" Results

"Cloudy Winter" Simulation Results (kW)	
P2P Trades	227,896
Self-Consumption	407,675
From Grid	4834,802
To Grid	0
Load Supplied	5470,373

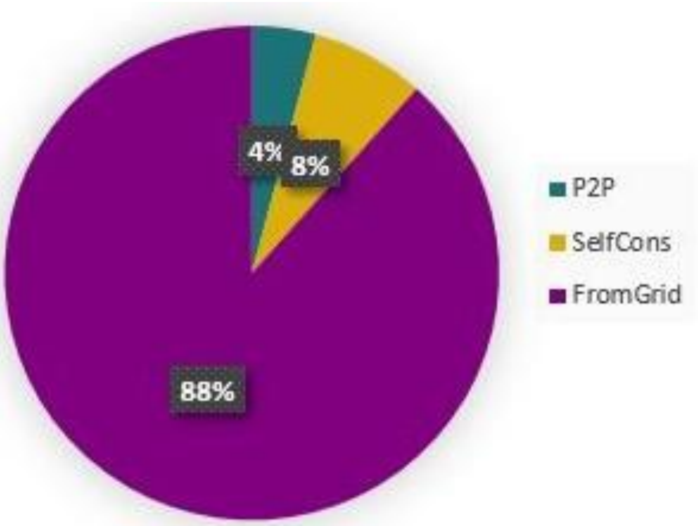

Figure 4.15 - "Cloudy Winter" total energy mix.

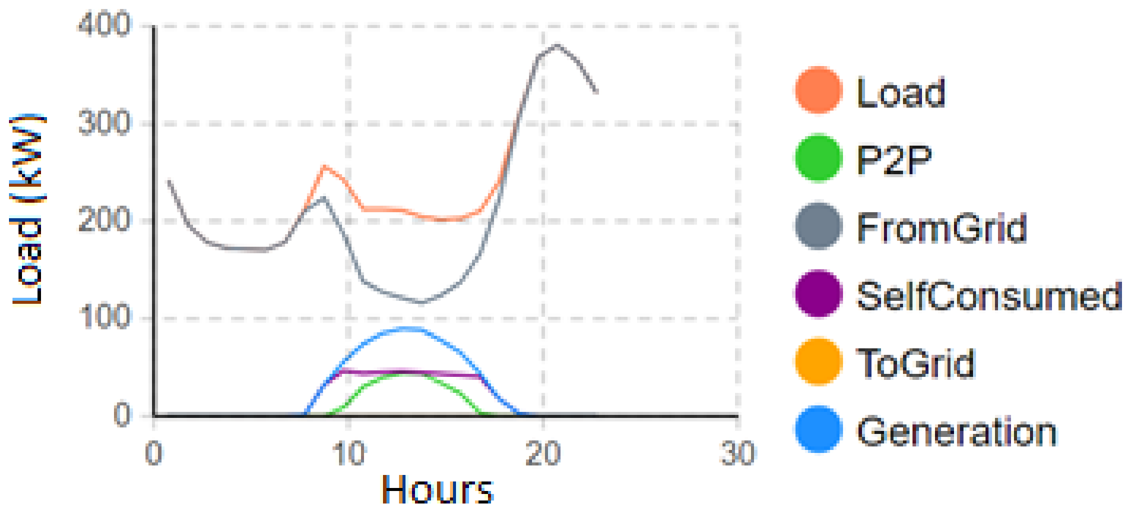

Figure 4.16 - "Cloudy Winter" energy mix.

The “Rainy Winter” simulation builds on the last one, testing the impact of the weather on the results. It is a "rainy” weather simulation, keeping the supplied load value close to the one of the previous winter simulation, but decreasing generation even further (Table 4.9). There is almost no generation in comparison to the load profile, and all of it is used for self-consumption, so there is no energy left for P2P trades (Figure 4.17). Thus, the population is almost completely dependent on the grid (96%) as can be seen in Figure 4.18, where the load and “FromGrid” curves almost overlap.

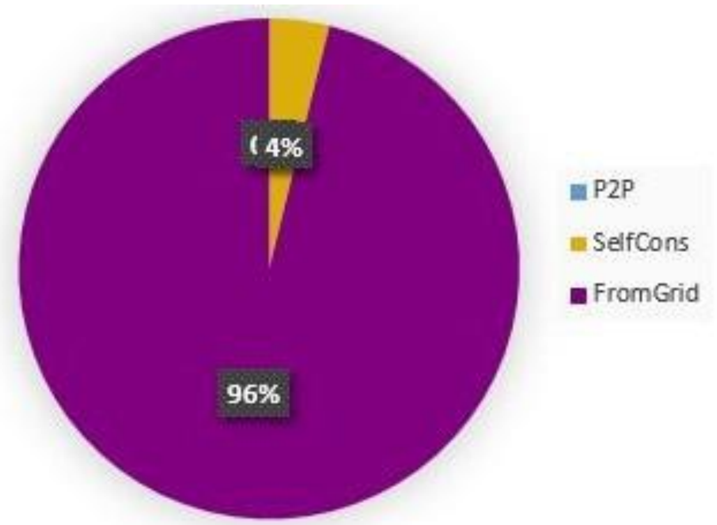

Figure 4.17 - "Rainy Winter" total energy mix.

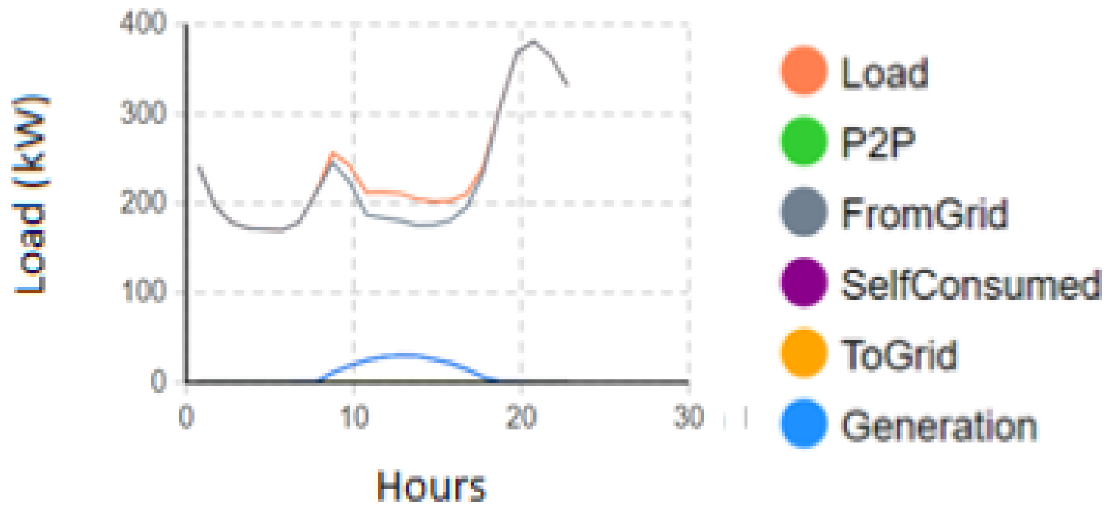

Figure 4.18 - "Rainy Winter" energy mix.

Table 4.9 - "Rainy Winter" Results.

"Rainy Winter" Simulation Results (kW)	
P2P Trades	0
Self-Consumption	211,857
From Grid	5258,516
To Grid	0
Load Supplied	5470,373

This shows the variability in the generation and dependence of the community on the weather to self-generate, consume, and trade energy.

4.4 Cost Analysis

Finally, the financial results were calculated to compare all cases. Costs associated with self-consumption were not calculated as operational and maintenance costs of PV panels were not considered.

Keeping in mind that these results have the benefit of the population as an objective, costs related to P2P transactions will be noted but not accounted as positive nor negative. While one member of the population is paying this value, another is gaining the same - as such, the population has no financial gain nor loss from the transaction.

Table 10 shows the cost analysis results of all simulations relative to the base case. In the situations where there was no surplus, no energy was sold to the grid and no currency was made. The same goes for the situation where no P2P transactions happened - there were no costs nor gains.

Only the "winter" scenarios had worse financial outcomes than the base case, with 19% and 29% higher costs from the grid.

Table 4.10 - Cost Analysis Relative to the Base Case.

	Base Case	C1 25%	C1 50%	C1 100%	C2 100%	C2 SS	C2 CS	C2 CW	C2 RW
Cost P2P Trades (€)	0	0	0	0	0	0	0	0	0
Cost From Grid (€)	1001.446	88.15%	75.06%	63.67%	50.25%	44.31%	53.78%	118.74%	129.04%
Revenue From Grid (€)	0	0	0.216	67.180	166.556	49.006	0	0	0
Total Cost (€)	1001.446	88.15%	75.06%	63.67%	50.25%	44.31%	53.78%	118.74%	129.04%
Decrease in Cost Including Revenue From Grid(€)	0	0	0.02%	6.71%	16.63%	4.89%	0	0	0

The simulations where the least money was spent on the grid were the two "summer" scenarios, with nearly half (49% and 54%) the costs relative to the base case. This speaks to the importance of not being able to store surplus or shift loads and is most likely the key to a more successful model. Summer scenarios were successful because the load was far less than in other cases, so when there was generation it was very likely to achieve positive results – technically and financially – which was verified.

In winter scenarios, given the lack of generation and increased load, negative results of 29% increase in costs (worst case), compare palely to the summer and year-average cases' positive outcomes of 12% reduced cost (worst case). Despite this model's generic nature and handicaps with lack of ESSs, shiftable loads and other types of generation, the model shows positive financial outcomes in almost all scenarios, bar the extreme, highly unfavorable ones.

These outcomes become even more visible when taking into account the energy sold to the grid. The simulations with a very high number of prosumers see significant changes in these cases - with 100% prosumers, the energy sold to the grid makes back almost 17% of all costs, meaning that the costs from the grid would be halved compared to the base case.

4.5 Discussion of Model Aspects

From the model analysis, it was noted that the data was processed in hourly time frames and averages. This will bring a degree of uncertainty to the results. Energy has to be delivered when requested, and non-immediate availability is a major fault. In light of this, when in a scope of 24 hours, 1-hour time frames can hide a lot of issues, such as the time that it takes for the communication between the agents and the market facilitator and to check for the availability of energy before going to the next alternative.

Another difficulty in translating this model to reality is that, as current legislation stands, for example, in Portugal, this model could not work solely on the basis that a prosumer would always make more money selling to the grid than to a fellow consumer. The price of selling to the grid is 90% of the hourly electricity market price, while if they sold to a neighbor they would get 45% of the same price. This could be managed by a new mechanism like the government subsidizing the other part of the price, which is in itself another discussion. It would decrease dependency on the grid and favor RES-based energy (which favors the government) but that would mean to keep relying on subsidies.

In the cases where surplus is being sold to the grid, particularly in large quantities, there should be a great benefit in adding storage or shifting the demand peak. It would most likely have a great impact on the results and should be further explored. For example, in Case 1 (50% prosumer presence) - the first time there is enough surplus to have energy sold to the grid: had there been storage, this energy could have been passed on to the next hour, increasing savings and decreasing dependency on the grid.

As another example, in Case 1 (100% prosumer presence): energy is not bought from the grid from before 10 am until around 6 pm, but as the highest peak of the demand curve comes at hours when there is no generation, there is always a big dependency on the grid. The only way to change this would be to shift part of the load or store energy.

4.6 - Chapter Summary

This chapter contains results and analysis on progressively varying scenarios of the model, branching from a base case with 100% consumers (the closest to reality, broadly speaking, at the time of writing). The integration of prosumers follows, with four different levels of integration (25%, 50%, 75% and 100%). The last scenarios are variations of the 50% prosumer integration case, but with varying season and weather inputs Affecting generation.

Finally, a cost analysis was made to translate these results into "more palpable" values from a consumer point of view, and some conclusions of the model analysis were drawn.

Chapter 5

Conclusion and Future works

In this fifth chapter, the conclusions of the dissertation are described, along with some future works that may come from the development of this project, to improve the various issues tackled or others identified that did not affect this work specifically because of the assumptions made. Finally, the contributions of this thesis are emphasized by the publication that came from this work.

5.1 Conclusions

In this work, an Agent Based model was presented to examine the effects of increased consumer participation within a local energy system. This model utilizes a diverse set of consumers based on real-world data to model and provides insight into the interactions within a P2P energy trading system. The effects of P2P trading on financial outcomes as well as the share of renewable energy utilized within the local energy system was investigated.

The model proved to be feasible even in the most generic conditions and lacking supportive but expensive technology such as electrical energy storage, in some conditions even reaching 50% savings and lessening strain from the grid. Also, the highest percentage of P2P energy traded in these conditions would likely be with somewhere between 50 to 75% prosumers. That balance is where the model would reach most success.

Nevertheless, 25% prosumer presence already had considerable impact and could be a reasonable starting point. 75% prosumer presence was the best scenario analysis. After this point, we saw a drop in the efficiency of the model.

The sensitivity analysis proved that the model should still be viable and preferable during the summer months even if the weather is not ideal. However, the model is not season and weather proof, and months with higher-than-average demand curves and lower than average generation profiles could render the model near redundant.

Based on the results and discussion, the Agent Based models can accurately model P2P energy trading systems and can capture the effects of individual behavior of a large number of active consumers within electrical systems.

5.2 - Future Works

As for future works, considering this subject:

- Adding Energy Storage Systems;
- Analyzing the results with smaller time frames;
- Introducing shiftable loads and electric vehicles;
- Introducing other types of RESs;
- Exploring pricing alternatives for P2P trade given incompatible legislation with the price for selling to the grid;
- Introducing load and generation variability per time frame and per agent, instead of per percentage of the population.

5.3 - Works Resulting from this Dissertation

D. V. Guimarães, M. Gough, S.F. Santos, J.P.S. Catalão, "***Agent-Based Modeling of Peer-To-peer on Smart Grid Environment***", in: Proceedings of the 21th IEEE International Conference on Environment and Electrical Engineering and 5th IEEE Industrial and Commercial Power Systems Europe — EEEIC 2021 / I&CPS Europe 2021, Bari, Italy, 7-10 September, 2021 (**accepted**).

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